Bits are Cheap, Atoms are Expensive: Critiquing the Turn Towards Tangibility in HCI

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Ever since the introduction of the desktop interface, HCI has strived to develop alternatives that make interacting with computers more physical, embodied and ubiquitous. In particular, the vision of tangible user interfaces (TUI) has had a large impact and inspired an extensive body of research over the last 25 years. However, despite strong interest from the research community, commercial success has been limited. We argue that the reason is that whereas graphical user interfaces are inherently *cheap*, physical interfaces are *expensive:* to *create;* to *control;* to *modify;* to *maintain;* and to *mass-produce and distribute*. This also leads to TUIs being highly problematic from a sustainability viewpoint. Finally, as a way to combine the best of both worlds, we introduce a vision of *liberated pixels,* which are visual output elements that are *perceivable, addressable,* and *persistent* in the physical world.

CCS CONCEPTS • Human-centered computing~Human computer interaction (HCI)~Interaction paradigms • Human-centered computing~Ubiquitous and mobile computing~Ubiquitous and mobile computing theory, concepts and paradigms • Human-centered computing~Human computer interaction (HCI)~HCI theory, concepts and models

Additional Keywords and Phrases: Tangible user interfaces, embodied interaction, ubiquitous computing, future of HCI, sustainability, liberated pixels

1 INTRODUCTION

The concept of *tangible user interfaces* (TUI) was introduced 25 years ago as a vision to go beyond the then-prevalent desktop computer interface and “create seamless interfaces between people, bits and atoms”. [19] In a highly influential paper, Ishii and Ullmer [ibid.] presented an approach to the interaction between humans and digital information, where digital “bits” were instantiated not as ephemeral pixels on a screen, but as real, graspable, physical objects. This approach allows for a whole new way of designing human-computer interfaces, that takes into account all of the human senses, not just the visual, and that integrates with the physical environment in a way the desktop computer arguably could not. In the years since its initial publication, the concept of tangible user interfaces has had a great impact on the field of human-computer interaction (HCI), and a large number of research papers have been published that are directly or indirectly influenced by this paradigm.

Yet despite the undeniable influence of the tangible user interface paradigm in HCI research, the number of examples of TUIs in real-world products is still surprisingly small, and mostly limited to research prototypes or bespoke installations, e.g. in museums. At the same time, in the decades since TUIs were first introduced, we have also seen an explosion in new mobile and ubiquitous products and services, the most successful being the smartphone, which is used by an estimated 83% of the world’s population.[1] Thus the modern smartphone, with

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[1] https://www.bankmycell.com/blog/how-many-phones-are-in-the-world

its touchscreen-based graphical user interface, has become the de facto way in which computing has been brought "off the desktop".

In this article, we will argue that there are a number of fundamental issues that stand in the way of tangible user interfaces becoming widely successful, and until those are solved (which may never happen in some cases) pixel-based graphical user interfaces – or *bits* – are going to be superior to physical interfaces – *atoms* – for many purposes. Furthermore, *if* tangibles were to become popular in mass-market devices, this could lead to unprecedented sustainability issues, which have so far not been acknowledged in the TUI literature. This is because many tangible electronic devices are made from raw materials that are sometimes rare and often not recyclable; they need to be manufactured and shipped in large quantities which consumes energy and packing materials; and they often also require their own power-source in the form of batteries, which are a major environmental hazard in themselves. Finally, we discuss a possible way forward by letting bits break out into the real world, which we call *liberated pixels.*

But to understand where TUIs came from and where they may be going, as well as what impact they may have in the future, we first need to look back at a time when HCI researchers were actively searching for novel interaction techniques – beyond the established desktop computer paradigm.

2 A BRIEF HISTORY OF THE FUTURE OF HUMAN-COMPUTER INTERACTION

An article from 2006 by John Canny provides a useful snapshot of the future of human-computer interaction as seen 16 years ago. [4] This was at a time when the desktop computer and the graphical user interface had become well established, but just before the introduction of the first widely successful smartphone with touchscreen and a graphical user interface.2

The author claims that the WIMP (for Windows, Icons, Mouse and Pointers) interface, as incubated at Xerox PARC in the 1970s as the Alto, and commercialized as the Xerox Star computer in 1981, was in a way "too good".3 When the essentials of the WIMP interface were incorporated in the design of the Apple Macintosh that was introduced in 1984, it effectively became the blueprint for all future personal computers (including the PC, through Microsoft's release of Windows 95). According to Canny, the narrative goes something like this: "HCI hasn't produced major innovations in the last 20 years; the WIMP interface today is almost identical to what it was in the 1980s." [ibid] However, the author also notes that in many technical fields, if a design has survived for 20 years (and today, more like 40!) it would be considered a compliment rather than a failing. He attributes this longevity to the fact that humans are the key element in HCI, and "as a species, people don't evolve that fast, and we often take years to learn things well." [ibid.] Canny goes on to posit that *context awareness* and *perceptual interfaces* will be major factors in future (i.e. post-2006) HCI. He calls them "two sides of the same coin" [ibid.] as they involve using various cues besides direct input to find out what the user wants in a given situation.

However, despite major advances in perceptual interfaces, in particular voice and image recognition, the main interaction mode for desktop computers, as well as mobile devices such as smartphones, still remains a graphical user interface. Products such as Apple's Siri, Microsoft's Cortana, Google's Duplex, and Amazon's Alexa have had some success, but perceptual interfaces and context awareness have (at least so far) not become the dominant form of interaction in HCI that Canny and others predicted. Instead, the touchscreen (already well known by 2006 but popularized by smartphones and tablets soon after) has been the most prevalent new user interface component in what we could call "post-WIMP" devices (while acknowledging that WIMP-based desktop and laptop computers are still widely used).

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2 The Apple iPhone was announced in a keynote on January 9, 2007 and went on sale on June 29, 2007. Although several phones had used touchscreens before, they had been aimed mainly at business users and had relatively little success with consumers.

3 The roots of the WIMP interface can be traced back further, to Vannevar Bush's "memex", J. C. R. Licklider's vision of man-machine symbiosis, and Douglas Engelbart's 1968 "Mother of All Demos." For a fuller account, see [15].

But what were some of the other alternatives that have been presented in HCI to go “beyond the desktop”? The timing of Canny’s article is interesting since in 2006, there had actually already been several HCI paradigms proposed as alternatives to WIMP. Probably the most influential one that was explicitly aiming to go “beyond the desktop computer” was presented about 15 years before Canny’s article. Introduced in 1991, *ubiquitous computing* was predicted to be the “third wave” of computing, after mainframes and personal computers. [41] In 1993, Mark Weiser, “the father of ubiquitous computing”, stated that “in the long run, the personal computer and the workstation will become practically obsolete because computing access will be everywhere: in the walls, on your wrist, and in ‘scrap’ computers (i.e., like scrap paper) lying about to be used as needed.” [42] Although the personal workstation did not actually become obsolete, much of the rest of the vision has been realized in the form of new product categories such as internet-connected smartphones, tablets, and smartwatches, as well as embedded computing devices and the Internet of Things. It has also given rise to a large body of computer science and HCI research, as well as numerous specialized conferences and workshops from the mid-1990s onwards, including the annual *ACM Ubicomp* conference since 1999.

Another new and highly influential HCI concept introduced in the 1990s was *tangible user interfaces (TUI).* [19] This notion is closely related to ubiquitous computing, as well as building on other then-current concepts such as graspable user interfaces [11] and augmented reality. [43] The TUI concept was first introduced in a paper by Ishii and Ullmer of the MIT Media Lab at the ACM CHI conference in 1997, in a session called *Beyond the Desktop*.[4] Since then, the concept has generated a large body of research papers (estimated to more than 3,500 at the time of writing[5]), a dedicated conference series (*ACM Tangible, Embedded and Embodied Interaction,* TEI, since 2007) and a number of journal special issues. As a credit to its influence and longevity, TUI originator Hiroshi Ishii was given a *Lifetime Research Award* at CHI 2019 for his work. [18]

In the paper that introduced tangible user interfaces, entitled *Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms,* the authors wanted to build on the earlier visions such as ubiquitous computing:

To make computing truly ubiquitous and invisible, we seek to establish a new type of HCI that we call “Tangible User Interfaces” (TUIs). TUIs will augment the real physical world by coupling digital information to everyday physical objects and environments. [19]

It is hard to overstate how influential this vision would almost immediately become in the HCI field. Although it had been preceded by other examples of how to make digital information tangible (such as Durrell Bishop’s conceptual *Marble Answering Machine* [8]), Ishii and Ullmer’s paper synthesized this nascent direction in HCI and gave it an immediately recognizable name and context. Furthermore, in addition to presenting the framework for this new style of interfaces, the paper also included a number of compelling and fully implemented examples, that were significant contributions in themselves. This included the *metaDESK,* a table-based visualization of a geographic area that included a number of tangible interaction modes including physical lenses that could reveal information, and phicons (physical icons) representing landmarks; [38] and the *ambientROOM*, which provided the user with peripheral information that could be controlled with phicons representing different forms of data sources such as road traffic. [21]

The initial paper was followed by what can only be described as an explosion in tangible user interfaces, both from the original authors and many others who picked up the concept. We are not able to give a full account of the research field in this text, but its vast and continuing influence can be confirmed by the fact that the original paper by Ishii and Ullmer is currently the most cited of all papers published in the CHI proceedings, and among the most cited papers of all SIGCHI-sponsored published publications.[6]

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[4] The CHI 1997 paper session *Beyond the Desktop* contained only two papers, with the other presenting a generic software architecture model for computer-supported collaborative work. There was also a Technical Notes session with the same title with an additional 2 short papers.

[5] The ACM Digital Library search *[All: "tangible interface"] OR [All: or] OR [All: "tangible interfaces"] OR [All: or] OR [All: "tangible user interface"] OR [All: or] OR [All: "tangible user interfaces"] AND [Publication Date: (01/03/1997 TO 30/04/2022)]* had 3,878 results in December 2022.

[6] This number is based on an ACM Digital Library search in December 2022 of all articles published in the CHI proceedings and SIGCHI-sponsored venues, respectively, ordered by citations and discounting collections (i.e. proceedings). For refence, the two higher cited SIGCHI papers are Deterding et al. [5] (3065 citations) and Resnick et al. [34] (3022 citations) vs. Ishii and Ullmers’ 2115. Other searches (e.g. Scopus, Google Scholar) would obviously give different citation numbers, but the trend is the same.

3 TANGIBLE USER INTERFACES IN THE REAL WORLD

While the influence of tangible interfaces on the field of HCI research is undeniable, their real-world impact is less easy to ascertain. Most directly stemming from the original work, a number of companies were created to commercialize the research on tangible user interfaces at the MIT Media Lab. This included *Topobo*, a construction toy with kinetic memory; and *Sifteo Cubes*, a gaming platform consisting of motion-aware cubes with touchscreens. [26][31] However, despite promising user tests and being enthusiastically received by the public and media in demonstration settings, both companies have ceased trading.7 8 Another company that has apparently stopped trading was *Ambient Devices,* which sold products inspired by the concept of ambient media (also introduced in the original tangible bits paper), such as *The Ambient Orb,* a globe-like device that could glow in different colors to reflect e.g. the weather or the stock market.9 A look at their still-existing website also shows that the products the company was selling by 2014 had ventured far from the original concept of ambient media, and instead consisted mostly of screen-based information dashboards.

As for other TUI-based products, it partly depends on the definition of tangible user interfaces in the first place. Some sources include the computer mouse in the TUI category,10 but we feel this is questionable as the stated purpose of tangible user interfaces was to go “beyond the desktop” interface. The *Surface Dial* by Microsoft was seen as an example of a successful tangible interface and mentioned as such in a CHI 2019 panel on the future of TUI. [17] The Dial was introduced in 2017 and is a customizable physical knob that can be associated with a variety of different software control functions. It is still for sale and seems well-received by consumers, although it would have to be considered a niche product. As for other examples, our online searches for tangible user interface products have mostly turned up articles from ten or more years ago, and we have had trouble finding any consumer-oriented devices that truly embody the idea of tangible user interaction, where digital bits are represented and/or controlled in a physical interface – at least if we want to go beyond standard physical buttons or dials.

The situation is more promising in the bespoke exhibition sphere. Some of the most well-known examples come from the field of interactive music installations, such as the *reacTable.* [23] This was an example of using physical pucks (in a similar way to the phicons of the original metaDESK) to control a musical performance. The reacTable was exhibited at many galleries and conferences, and a company was set up to launch several products including a mobile version, although that also seems to have stopped trading and the app has not been updated for several years.11 Although it was apparently not widely adapted by musicians, it was used by leading artists such as Björk. [44] Another area where tangible interfaces have been popular is in education, in particular in a number of toolkits and platforms for building physical-digital installations. The *Arduino12* and *Raspberry Pi13* are both widely used microcomputers that can be used to prototype physical interaction, but they are more used in teaching and one-off installations, and generally are not found in consumer products for end-users. In a similar way, *Phidgets14* and *LEGO Mindstorms15* allow users to construct fully interactive physical installations through connecting blocks with different functionality including sensors and actuators, but again the end-results are usually not suitable for sustained use. The widespread availability at educational institutions of 3D printers and other rapid fabrication methods have also made the production of tangible interfaces more accessible, although such objects are generally produced in single instances or small series (e.g. [22][40]). Finally, an educational

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7 Topobo website (still existing but non-active): https://topobo.com

8 Sifteo Cubes at Wikipedia: https://en.wikipedia.org/wiki/Sifteo_Cubes

9 The company’s website http://www.ambientdevices.com still exists, but no news have been posted since 2014, and an online search for the company’s signature products (e.g. The Ambient Orb) turns up no availability to purchase.

10 From the Wikipedia page *Tangible User Interface:* “A simple example of tangible UI is the computer mouse: Dragging the mouse over a flat surface moves a pointer on the screen accordingly.” https://en.wikipedia.org/wiki/Tangible_user_interface

11 C.f. http://reactable.com

12 https://www.arduino.cc

13 https://www.raspberrypi.org

14 https://www.phidgets.com

15 https://www.lego.com/en-gb/themes/mindstorms

installation that is an example of tangible user interfaces in widespread exhibition use is the *Augmented Reality Sandbox* which was open-sourced by UC Davis, and has been installed in many museums around thew world. [32]

4 BITS ARE CHEAP, ATOMS ARE EXPENSIVE

We must at this point stress that the above is in no way meant as a criticism of the concept of tangible user interfaces itself. The influence of TUI in HCI research is undeniable, and has directly or indirectly inspired an impressive array of novel inventions and interface technologies that will have lasting impact in themselves. However, we do think it is clear that TUI has struggled in the transition from research to product, and this article is partly an attempt to identify why this is and how it can be rectified. As mentioned, in the last decade the smartphone with its touchscreen GUI has become the dominating interaction paradigm to go "beyond the desktop", and thus reached even more people than the personal computer. It is important to acknowledge that many of the vital UI components of the smartphone also came directly out of a long history of HCI-related research: The arguably first successful smartphone, the iPhone, was originally envisioned as a tablet, which was clearly inspired by the Ubiquitous Computing project at Xerox PARC that produced the ParcPad tablet; [12] and technologies and interaction modes for multitouch screens had a long history in academic research before they were instantiated in this and other successful consumer products (e.g. [6][14][33]).

So what does this say about TUIs? According to Bill Buxton's theory of "the long nose", "any technology that is going to have significant impact in the next 10 years is already at least 10 years old." [3] What this means is that rather than arriving fully formed and ready to go into products, any new technology will actually take many years of refinement before it is commercially viable – even longer before it reaches a large-scale market. Buxton uses examples that are very relevant to our case, including the mouse, which was developed in the 60's and 70's, commercialized in the 80's, but did not become ubiquitous until the 1990s with the release of Windows 95. [ibid.] Another example is the capacitive multitouch interface, which was published as early as 1985 and turned up in products over 20 years later, in the Apple iPhone and then many other smartphones and tablets. This observation is not unique for digital technology, but is in fact consistent across other fields as well. [9]

Given this timeline for innovation, and the large number of papers that have been published in the 25+ years since the paradigm was introduced, it seems reasonable to expect that there would by now be a multitude of successful tangible user interfaces in the hands of users. But as we saw in the last section, these have yet to materialize, at least at a large consumer scale. If anything, interacting with computers has become *less* physical in the last 15 years, as much of it is now done through touchscreen devices that no longer need a mouse or keyboard. One reason for this lack of products stemming from research may be that TUI is not a single technology, but rather a wide-ranging concept with many possible instantiations and implementations. This has meant that unlike say multitouch, there has not been a refinement towards a single well-defined final form, but rather a multitude of diverse examples that all embody the concept in one way or another, across many different application domains and technologies.

But another reason why TUIs are not as widespread as the GUI they were supposed to complement, or even replace, fundamentally have to do with how they are implemented. Just as stated in the original paper, TUIs are made of atoms, as opposed the bits that make up the pixels of a graphical user interface. And the fact is that physical things – especially *interactive* physical things – are orders of magnitude more difficult to build and manage than virtual things, represented by pixels on a screen. In other words, atoms are very *expensive* compared to bits. This does not only mean that devices based on tangible user interfaces may cost more for a consumer, it means that they are expensive in a multitude of ways that GUI-based interfaces are not. We argue that TUIs are significantly more expensive to *create;* to *control;* to *modify;* to *maintain;* and to *mass-produce and distribute* than GUI-based systems. In the following we will break down these inherent costs of tangible user interfaces, followed by a discussion on what may be the greatest cost of all, the repercussions for the environment.

First, it has been widely acknowledged in the research community that tangible user interfaces are more expensive to *create,* both with regards to implementation time and actual cost, than GUIs. Because of a lack of standardized UI components, prototyping and testing new TUIs has taken longer time and more effort than GUIs, for which there are already many established software frameworks. To rectify this, several prototyping environments for TUIs that are inspired by GUI environments have been proposed (e.g. [13]), and as mentioned before, the availability of rapid manufacturing has also made producing physical objects more accessible. However, the lack of standardized tools and methods for creating TUIs is still an issue that is hindering their development.

Second, and more fundamentally, TUIs are more expensive to *control*. Whereas the appearance and function of a pixel can be changed in almost no time with negligible cost, atoms are much less malleable. To rapidly change the physical shape or even the visual appearance of a physical object can be technically extremely difficult, and therefore there are very few examples of truly dynamic physical user interfaces. Instead, a common solution is to provide an associated pixel-based output, either a projection or a screen, with screen-based examples such as the metaDESK and Reactable mentioned above, or projection-based solutions such as the AR Sandbox. Solutions that are more true to the tangibility aspect include various techniques such as motors, hydraulics, or piezoelectric materials to affect the shape of an object, however, these still remain at the research stage for the most part. [36] Conversely, the registering of user input is also difficult on a physical object, although techniques such as capacitive [30] or radio-based [25] sensing might be used, as well as deformable objects. [2] Thus, despite futuristic proposals such as *radical atoms* [20], the lack of truly dynamic physical interfaces will remain a major issue for TUIs in the foreseeable future.

A third issue is that TUIs are more expensive to *modify* after the fact. Whereas to update a graphical user interface is easily done through a downloadable software patch, an update to a TUI may require entirely new physical components, which have to be produced and distributed. This makes it very difficult to provide new features or fine-tuning to an existing TUI, something that in a world where major software systems are often updated on a weekly basis makes it very hard to keep up. It also means that it is extremely important to get a TUI right the first time to avoid expensive updates, whereas a GUI-based system will have much more leeway to refine and add UI functionality throughout its lifetime.

The fourth issue is that TUIs are more expensive to *maintain*. Whereas pixels are for all intents indestructible and will last forever (as long as there is a working display), TUIs are highly susceptible to wear and tear, as well as mechanical and electronic malfunction, leading ultimately to a potential loss of functions or even a full breakdown. This will by necessity lead to requiring the repair and possibly replacement of components, which is made worse by the fact that TUIs are for the most part bespoke, i.e. they only perform one or a small set of functions. Thus, for each application there may potentially be a separate set of TUIs which need to be maintained and repaired, unlike for GUI-based applications where it is only one device (e.g. phone or computer) that is responsible for all functions. This is probably the reasons that many of the successful examples of TUIs we have seen are made for limited, controlled settings such as museums, where they can be attended to by dedicated staff and repaired if necessary.

Finally, TUIs are expensive to *mass-produce,* as well as to *distribute* to end-users. Whereas software can be easily duplicated on storage media and distributed through wired or wireless networks at low or even negligible cost, physical objects require manufacturing and shipping to reach a user. This is likely another reason why most successful examples of TUI can be found as site-based installations or single-instance prototypes rather than consumer products. Although the step from prototype to product is not by any means trivial in software, it is many orders of magnitude more difficult for physical products. Thus, while software makers can have a variety of pricing models to make them attractive to different users, such as subscription models, try-before-you-buy, or even free, a physical product will have a much higher built-in initial cost. On the other hand, smartphones and tablets, while expensive, can perform a multitude of functions and thus are platforms for software apps rather than single-purpose devices, making them a much better value-proposition than TUIs that are limited to a single or only a few uses.

5 SUSTAINABILITY AND TANGIBLES

We argue that all the above qualities of tangible user interfaces lead to one final but extremely important meta-issue: *Tangible user interfaces are not sustainable.* In the last decade, sustainability has surfaced as a major issue in IT. The impact of large data centers, particularly for cryptocurrency mining but also for e.g. search, streaming and social networking, is well-known. Another part of the impact has to do with the prevalence of smartphones and other mobile devices: with literally billions of complex hand-held computers being produced and sold every year, e-waste (electronic waste) has become a massive problem. Phones in particular contain not only rare metals and potentially toxic materials, they are also based on rechargeable batteries which have a very strong adverse environmental impact if not recycled. Major companies such as Apple have made very public efforts to lower their environmental footprint by introducing trade-in and free recycling schemes. However, the issue is accelerated by the fact that these products have a built-in obsolesce and are meant to be replaced every few years. Many manufacturers also make it difficult or impossible for third parties to service and replace certain parts like the battery. This has been made even worse by the introduction of wireless peripherals such as Bluetooth headphones, which also contain batteries that are very hard to replace even though they have a strictly limited lifetime. [28] Movements such as *Right to Repair* have sprung up to give consumers more control over the longevity of electronic products and in some cases also resulted in new legislation forcing companies to open up their system for third-part parts and repair.

This discussion is highly relevant for tangible user interfaces. Just like phones and earbuds, many of these artifacts will contain advanced electronic components as well as batteries. One would therefore expect the environmental impact of TUIs to have been the subject of some discussion in the HCI community. However, we could find almost no mention of sustainability in relation to tangible user interfaces in the research literature except a panel from CHI 2019 and an accompanying ACM Interactions article. [16][17] We argue this is a major omission and needs to be rectified by the research community if TUIs are ever to become a credible alternative to GUIs. After all, if tangible user interfaces were to replace graphical user interfaces in everyday consumer products, the environmental impact would be massive. Rather than speaking about a few computational devices for each person (e.g. smartphone; earbuds; laptop or workstation) the vision of tangible bits, just like ubiquitous computing, might require hundreds or even thousands of computational devices per person. If we only include the developed world, this still means hundreds of billion devices that all need to be manufactured, shipped, installed, maintained and eventually disposed of. If even a low percentage of those go to e-waste rather than being recycled, we are potentially looking at an impact tens or hundreds of times of that which smartphones currently have.

Therefore, we strongly believe that if tangible user interfaces are to be genuinely considered as a UI paradigm with impact beyond the research community, there needs to be a serious discussion on the sustainability aspect. This could include using sustainable materials in the design and implementation of TUIs, and avoiding batteries and non-renewable materials; allowing for modification, upgrading and re-use as well as multiple functions to extend the lifetime and usefulness of a particular TUI; and having a strategy for the re-use or disposal of devices after they have served their original purpose. While these issues may have been less pressing in the early, exploratory years of the field, two and a half decades in they should really be close to the top on the list of concerns for any TUI researchers aiming to see their work used in the real world.

6 FROM TANGIBLE BITS TO LIBERATED PIXELS

So does this mean that all work on TUIs should be abandoned from now on? No, of course not. Literally thousands of research projects have shown that embedding digital information in the real world has many advantages, and the kind of embodied interaction (c.f. [7]) that TUIs make possible can involve the whole human body and all our senses, providing a much richer experience than that of the screen. But as we have also seen above, the many inherent costs of tangible user interfaces have meant that often, visually-based interfaces have been preferred in real-world products, even when a TUI solution might have provided a better experience overall. Furthermore, the introduction of mobile and handheld devices means that the vision of ubiquitous computing has already come true: instead of computers being confined to a desktop, today just about everyone has a networked computer in their pocket, with instant access to all the world's information, as well as being able to engage with work, social media and everyday tasks. Thus, unlike when TUIs were introduced, the pixel-based graphical user interface is now accessible almost everywhere in the physical world.

Yet, while pixels are great – they are inexpensive, dynamic, colorful, fast, and endlessly reusable – they have one major problem: *They are confined to a screen*. Visual computer displays have been refined and improved for over 60 years, from the early vector-based CRT screens of the 1960, through the bitmapped graphics of the 1970s, all the way to today's enormously fast and powerful high-resolution displays – using technologies such as LCD, LED, OLED, DLP, laser projection and more. However, even though today's displays come in almost any configuration, from pocket- to wall-size, they will still have an inherently limited physical area, and do not integrate well with the world around them.16 But what if the pixels that make up a visual user interface could somehow *break out* of the confines of a screen and bleed into the environment? Then they could take their place in the real world alongside all the human senses and physical experiences. This means we could combine the advantages of graphical user interfaces with those of the tangible. We call this approach *liberated pixels.*

The idea of letting pixels break free from their screens is not new. One of the early tangible bits projects at MIT proposed an infrastructure for freeing graphical displays and interaction from the confines of the screen, called the *Luminous Room.* This concept included a device called the *I/O Bulb,* envisioned as a light bulb that both projects and captures pixels. [39] Another example of placing pixels in the real world was *Everywhere Displays,* where a steerable data projector was able to project an image at an arbitrary location in a room. [29] There have also been examples of mobile projected displays, such as SixthSense, which used a wearable projector to project a graphical user interface in front of the user. [27] Modern smartphones and tablets are also capable of inserting computer graphics in real-world scenes using a variety of augmented reality APIs, such as Google's *ARCore* and Apple's *ARKit*. A similar effect can be achieved with head-mounted displays such as Microsoft's *Hololens* for industry use, or Nreal's *Air* smart glasses, which have recently been made available to consumers.

However, whereas the dominating industry AR paradigms are focused on providing an augmented experience to a single user, through a head-mounted display or a personal device, our ideal goes more towards the room-based approach of the Luminous Room or Everywhere Displays. This is because we would like to stay with the advantages of the shared physical world, as exemplified by tangible user interfaces as well as concepts such as amplified reality, which aims to "enhance the publicly available properties of a physical object." [10] What this means is that instead of creating an augmented world that is unique to the user of a particular head-mounted or handheld display, we would like to use our liberated pixels to create an interactive experience that is shareable among multiple users in the same physical space. It also needs to be possible to assign graphical elements to any object or location within that space, and these have to stay consistent over time as well as over different locations. From this follows that liberated pixels need to be *perceivable, addressable,* and *persistent* in the physical world, properties which current systems do not yet achieve.

Firstly, all users (both potential and actual) need to be able to *perceive* the pixels that make up an interactive system in the same way, without needing any kind of personal augmentation like a head-mounted display. Current projector and screen technology therefore needs to be re-thought to make possible displays that cover much larger areas without degradation in quality, or that can be moved or re-configured to present pixels everywhere they are needed. Second, to make pixels truly liberated means they need to be able to appear in any physical location, which means we need a way to make them individually *addressable* in the real world. Many augmented reality systems solve this by using either visual markers (e.g. [24]) or marker-less methods such as Visual SLAM [35], however, we are instead proposing something that is analog to 3D-version of a bitmapped display, where each point in space has a unique address in 3D space. Finally, users need to be able to trust that pixels stay put, even if for instance they leave the room and come back. This means that the pixels need to be *persistent* across

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16 This is also true for interaction paradigms such as augmented and mixed reality, as they rely on a head-mounted displays, handheld devices, or fixed projectors to insert digital graphics in the real world, approaches which all have their own limitations.

space and time, at least as long as an application is running. This requires the development of an overall interaction framework where visual interface components are integrated with physical space.

Taken together, realizing these properties would put pixels on equal footing with real-world, tangible objects, and make it possible to embed information and interactivity into all physical objects and locations. The resulting systems would have the advantage of pixels (cheap, fast, endlessly modifiable) as well as tangibles (physical, embodied, situated in the real world). However, to technically realize this vision requires significant advances in hardware, software and interaction frameworks. We therefore will now only propose the concept of liberated pixels as an initial vision for a new research direction, which will have to be further developed in future work.

7 CONCLUSION

In this article, we have explored why tangible user interfaces, despite being a major topic in HCI research during the last 25 years, have yet to make as much of an impact in real-world products as might have been expected. We stress that this is not intended as a criticism of the concept of TUI itself, which has inspired a large body of groundbreaking research, but rather an attempt to support their development by identifying the points that are holding them back from having more impact.

Our main observation is that while the *bits* that make up graphical user interfaces are in a sense “cheap” to create and distribute, *atoms* in the form of physical interactive artifacts are comparatively expensive. This notion of “expensive” does not only indicate the cost for an end-user to purchase a device or system, but it is comprised of many issues that have to do with the fundamental properties of TUIs. Unless these issues are solved, we think it is likely that graphical user interfaces will continue to be chosen and implemented over TUIs, even in cases where a tangible solution might give a better user experience. We also come to the conclusion that TUIs are currently not sustainable, and researchers need to engage with this issue if they want them to have a wider impact without the associated environmental and e-waste issues associated with other electronic products.

To move forward, we believe the field of tangible user interfaces will need to critically engage with the underlying issues we have identified here. Fundamentally, this means finding ways of producing TUIs that are cheaper – in the sense that they are easier to create, control, maintain, mass-produce and distribute, and have a smaller environmental footprint. A potential solution is to look at the success of graphical user interfaces and consider how pixels, which currently are confined to screens, could break free and start to fully engage with the physical world. We call this concept *liberated pixels,* but although some of the building blocks already exist, there is much research to be done to make this vision become a reality.

REFERENCES

<bib id="bib1"><number>[1]</number> BGR.in. April 14, 2022. Apple and Meta to launch AR glasses by 2024: Expected price, specifications and more. https://www.bgr.in/wearables/apple-and-meta-to-launch-ar-glasses-by-2024-expected-price-specifications-and-more-1257249/</bib>
<bib id="bib2"><number>[2]</number> Alberto Boem and Giovanni Maria Troiano. 2019. Non-Rigid HCI: A Review of Deformable Interfaces and Input. In Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19). Association for Computing Machinery, New York, NY, USA, 885–906. DOI:https://doi.org/10.1145/3322276.3322347</bib>
<bib id="bib3"><number>[3]</number> Bill Buxton. 2008. The Long Nose of Innovation. Businessweek, 2 January 2008. https://www.bloomberg.com/news/articles/2008-01-02/the-long-nose-of-innovationbusinessweek-business-news-stock-market-and-financial-advice Revised version available at http://www.billbuxton.com/01%20The%20Long%20Nose%20of%20Innovation%20Revised.pdf</bib>
<bib id="bib4"><number>[4]</number> John Canny. 2006. The Future of Human-Computer Interaction: Is an HCI revolution just around the corner? Queue 4, 6 (July-August 2006), 24–32. DOI:https://doi.org/10.1145/1147518.1147530</bib>
<bib id="bib5"><number>[5]</number> Sebastian Deterding, Dan Dixon, Rilla Khaled, and Lennart Nacke. 2011. From game design elements to gamefulness: defining "gamification". In Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments (MindTrek '11). Association for Computing Machinery, New York, NY, USA, 9–15. DOI:https://doi.org/10.1145/2181037.2181040</bib>
<bib id="bib6"><number>[6]</number> Paul Dietz and Darren Leigh. 2001. DiamondTouch: a multi-user touch technology. In Proceedings of the 14th annual ACM symposium on User interface software and technology (UIST '01). Association for Computing Machinery, New York, NY, USA, 219–226. DOI:https://doi.org/10.1145/502348.502389</bib>
<bib id="bib7"><number>[7]</number> Paul Dourish. Where the Action Is: The Foundations of Embodied Interaction. MIT Press (20 Aug. 2004)</bib>
<bib id="bib8"><number>[8]</number> Pierre Dragicevic and Yvonne Jansen. List of Physical Visualizations and Related Artifacts: 1992 – Durrell Bishop's Marble Answering Machine. http://dataphys.org/list/durrell-bishops-marble-answering-machine/</bib>

<bib id="bib9"><number>[9]</number> Peter Drucker. 2007. Innovation and Entrepreneurship. London: Routledge. https://doi.org/10.4324/9780080549415</bib>
<bib id="bib10"><number>[10]</number> Jennica Falk, Johan Redström, and Staffan Björk. 1999. Amplifying Reality. In Proceedings of the 1st international symposium on Handheld and Ubiquitous Computing (HUC '99). Springer-Verlag, Berlin, Heidelberg, 274–280.</bib>
<bib id="bib11"><number>[11]</number> George W. Fitzmaurice, Hiroshi Ishii, and William A. S. Buxton. 1995. Bricks: laying the foundations for graspable user interfaces. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '95). ACM Press/Addison-Wesley Publishing Co., USA, 442–449. DOI:https://doi.org/10.1145/223904.223964</bib>
<bib id="bib12"><number>[12]</number> Forbes. Apr 16, 2013. A Visit To Xerox PARC. https://www.forbes.com/pictures/elee45hkej/the-xerox-parcpad/</bib>
<bib id="bib13"><number>[13]</number> Saul Greenberg and Chester Fitchett. 2001. Phidgets: easy development of physical interfaces through physical widgets. In Proceedings of the 14th annual ACM symposium on User interface software and technology (UIST '01). Association for Computing Machinery, New York, NY, USA, 209–218. DOI:https://doi.org/10.1145/502348.502388</bib>
<bib id="bib14"><number>[14]</number> Jefferson Y. Han. 2005. Low-cost multi-touch sensing through frustrated total internal reflection. In Proceedings of the 18th annual ACM symposium on User interface software and technology (UIST '05). Association for Computing Machinery, New York, NY, USA, 115–118. DOI:https://doi.org/10.1145/1095034.1095054</bib>
<bib id="bib15"><number>[15]</number> Michael A. Hiltzik. 2000. Dealers of Lightning: Xerox PARC and the Dawn of the Computer Age. Harper Business.</bib>
<bib id="bib16"><number>[16]</number> Lars Erik Holmquist. 2019. The future of tangible user interfaces. interactions 26, 5 (September-October 2019), 82–85. DOI:https://doi.org/10.1145/3352157</bib>
<bib id="bib17"><number>[17]</number> Lars Erik Holmquist, Oren Zuckerman, Rafael Ballagas, Hiroshi Ishii, Kimiko Ryokai, and Haiyan Zhang. 2019. The Future of Tangible User Interfaces. In Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (CHI EA '19). Association for Computing Machinery, New York, NY, USA, Paper panel02, 1–6. DOI:https://doi.org/10.1145/3290607.3311741</bib>
<bib id="bib18"><number>[18]</number> Hiroshi Ishii. 2019. SIGCHI Lifetime Research Award Talk: Making Digital Tangible. In Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (CHI EA '19). Association for Computing Machinery, New York, NY, USA, Paper Award1, 1–4. DOI:https://doi.org/10.1145/3290607.3313769</bib>
<bib id="bib19"><number>[19]</number> Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In Proceedings of the ACM SIGCHI Conference on Human factors in computing systems (CHI '97). Association for Computing Machinery, New York, NY, USA, 234–241. DOI:https://doi.org/10.1145/258549.258715</bib>
<bib id="bib20"><number>[20]</number> Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical atoms: beyond tangible bits, toward transformable materials. interactions 19, 1 (January + February 2012), 38–51. DOI:https://doi.org/10.1145/2065327.2065337</bib>
<bib id="bib21"><number>[21]</number> Hiroshi Ishii, Craig Wisneski, Scott Brave, Andrew Dahley, Matt Gorbet, Brygg Ullmer, and Paul Yarin. 1998. AmbientROOM: integrating ambient media with architectural space. In CHI 98 Conference Summary on Human Factors in Computing Systems (CHI '98). Association for Computing Machinery, New York, NY, USA, 173–174. DOI:https://doi.org/10.1145/286498.286652</bib>
<bib id="bib22"><number>[22]</number> Michael D. Jones, Kevin Seppi, and Dan R. Olsen. 2016. What you Sculpt is What you Get: Modeling Physical Interactive Devices with Clay and 3D Printed Widgets. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16). Association for Computing Machinery, New York, NY, USA, 876–886. DOI:https://doi.org/10.1145/2858036.2858493</bib>
<bib id="bib23"><number>[23]</number> Sergi Jordà, Günter Geiger, Marcos Alonso, and Martin Kaltenbrunner. 2007. The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. In Proceedings of the 1st international conference on Tangible and embedded interaction (TEI '07). Association for Computing Machinery, New York, NY, USA, 139–146. DOI:https://doi.org/10.1145/1226969.1226998</bib>
<bib id="bib24"><number>[24]</number> Hideo Kato, M. Billinghurst, I. Poupyrev, K. Imamoto and K. Tachibana, "Virtual object manipulation on a table-top AR environment," Proceedings IEEE and ACM International Symposium on Augmented Reality (ISAR 2000), 2000, pp. 111-119, doi: 10.1109/ISAR.2000.880934.</bib>
<bib id="bib25"><number>[25]</number> Jaime Lien, Nicholas Gillian, M. Emre Karagozler, Patrick Amihood, Carsten Schwesig, Erik Olson, Hakim Raja, and Ivan Poupyrev. 2016. Soli: ubiquitous gesture sensing with millimeter wave radar. ACM Trans. Graph. 35, 4, Article 142 (July 2016), 19 pages. DOI:https://doi.org/10.1145/2897824.2925953</bib>
<bib id="bib26"><number>[26]</number> David Merrill, Jeevan Kalanithi, and Pattie Maes. 2007. Siftables: towards sensor network user interfaces. In Proceedings of the 1st international conference on Tangible and embedded interaction (TEI '07). Association for Computing Machinery, New York, NY, USA, 75–78. DOI:https://doi.org/10.1145/1226969.1226984</bib>
<bib id="bib27"><number>[27]</number> Pranav Mistry and Pattie Maes. 2009. SixthSense: a wearable gestural interface. In ACM SIGGRAPH ASIA 2009 Art Gallery & Emerging Technologies: Adaptation (SIGGRAPH ASIA '09). Association for Computing Machinery, New York, NY, USA, 85. DOI:https://doi.org/10.1145/1665137.1665204</bib>
<bib id="bib28"><number>[28]</number> Motherboard. AirPods Are a Tragedy. 2019-6-5. https://www.vice.com/en/article/neaz3d/airpods-are-a-tragedy</bib>
<bib id="bib29"><number>[29]</number> Claudio S. Pinhanez. 2001. The Everywhere Displays Projector: A Device to Create Ubiquitous Graphical Interfaces. In Proceedings of the 3rd international conference on Ubiquitous Computing (UbiComp '01). Springer-Verlag, Berlin, Heidelberg, 315–331.</bib>
<bib id="bib30"><number>[30]</number> Dominic Potts, Martynas Dabravalskis, and Steven Houben. 2022. TangibleTouch: A Toolkit for Designing Surface-based Gestures for Tangible Interfaces. In Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22). Association for Computing Machinery, New York, NY, USA, Article 39, 1–14. DOI:https://doi.org/10.1145/3490149.3502263</bib>
<bib id="bib31"><number>[31]</number> Hayes Solos Raffle, Amanda J. Parkes, and Hiroshi Ishii. 2004. Topobo: a constructive assembly system with kinetic memory. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04). Association for Computing Machinery, New York, NY, USA, 647–654. DOI:https://doi.org/10.1145/985692.985774</bib>
<bib id="bib32"><number>[32]</number> S. Reed, Kreylos, O., Hsi, S., Kellogg, L., Schladow, G., Yikilmaz, M.B., Segale, H., Silverman, J., Yalowitz, S., and Sato, E., Shaping Watersheds Exhibit: An Interactive, Augmented Reality Sandbox for Advancing Earth Science Education, American Geophysical Union (AGU) Fall Meeting 2014, Abstract no. ED34A-01 (2014)</bib>

<bib id="bib33"><number>[33]</number> Jun Rekimoto. 2002. SmartSkin: an infrastructure for freehand manipulation on interactive surfaces. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '02). Association for Computing Machinery, New York, NY, USA, 113–120. DOI:https://doi.org/10.1145/503376.503397</bib>
<bib id="bib34"><number>[34]</number> Paul Resnick, Neophytos Iacovou, Mitesh Suchak, Peter Bergstrom, and John Riedl. 1994. GroupLens: an open architecture for collaborative filtering of netnews. In Proceedings of the 1994 ACM conference on Computer supported cooperative work (CSCW '94). Association for Computing Machinery, New York, NY, USA, 175–186. DOI:https://doi.org/10.1145/192844.192905</bib>
<bib id="bib35"><number>[35]</number> Muhamad Risqi U. Saputra, Andrew Markham, and Niki Trigoni. 2018. Visual SLAM and Structure from Motion in Dynamic Environments: A Survey. ACM Comput. Surv. 51, 2, Article 37 (March 2019), 36 pages. DOI:https://doi.org/10.1145/3177853</bib>
<bib id="bib36"><number>[36]</number> Miriam Sturdee and Jason Alexander. 2018. Analysis and Classification of Shape-Changing Interfaces for Design and Application-based Research. ACM Comput. Surv. 51, 1, Article 2 (January 2019), 32 pages. DOI:https://doi.org/10.1145/3143559</bib>
<bib id="bib37"><number>[37]</number> Techradar. April 26, 2022. Nreal’s consumer-focused AR glasses are coming to the UK - but they have one limitation. https://www.techradar.com/news/nreals-consumer-focused-ar-glasses-are-coming-to-the-uk</bib>
<bib id="bib38"><number>[38]</number> Brygg Ullmer and Hiroshi Ishii. 1997. The metaDESK: models and prototypes for tangible user interfaces. In Proceedings of the 10th annual ACM symposium on User interface software and technology (UIST '97). Association for Computing Machinery, New York, NY, USA, 223–232. DOI:https://doi.org/10.1145/263407.263551</bib>
<bib id="bib39"><number>[39]</number> John Underkoffler, Brygg Ullmer, and Hiroshi Ishii. 1999. Emancipated pixels: real-world graphics in the luminous room. In Proceedings of the 26th annual conference on Computer graphics and interactive techniques (SIGGRAPH '99). ACM Press/Addison-Wesley Publishing Co., USA, 385–392. DOI:https://doi.org/10.1145/311535.311593</bib>
<bib id="bib40"><number>[40]</number> Aaron Visschedijk, Hyunyoung Kim, Carlos Tejada, and Daniel Ashbrook. 2022. ClipWidgets: 3D-printed Modular Tangible UI Extensions for Smartphones. In Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22). Association for Computing Machinery, New York, NY, USA, Article 8, 1–11. DOI:https://doi.org/10.1145/3490149.3501314</bib>
<bib id="bib41"><number>[41]</number> Mark Weiser, "The Computer for the Twenty-First Century," Scientific American, Vol. 265, No. 3, Sept. 1991, pp. 94-104.</bib>
<bib id="bib42"><number>[42]</number> Mark Weiser. 1993. Ubiquitous Computing. Computer 26, 10 (October 1993), 71–72. DOI:https://doi.org/10.1109/2.237456</bib>
<bib id="bib43"><number>[43]</number> Pierre Wellner, Wendy Mackay, and Rich Gold. 1993. Back to the real world. Commun. ACM 36, 7 (July 1993), 24–26. DOI:https://doi.org/10.1145/159544.159555</bib>
<bib id="bib44"><number>[44]</number> Scott Wilson. 2017. 7 times Björk used cutting-edge technology to shape her music. https://www.factmag.com/2017/11/24/bjork-technology-instruments-software/</bib>