Hybrid User Interfaces: Past, Present, and Future of Complementary Cross-Device Interaction in Mixed Reality

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(Survey Paper)

***Abstract*—We investigate hybrid user interfaces (HUIs), aiming to establish a cohesive understanding and to adopt consistent terminology for this nascent research area. HUIs combine heterogeneous devices in complementary roles, leveraging the distinct benefits of each. Our work focuses on cross-device interaction between 2D devices and mixed reality environments, which are particularly compelling, leveraging the familiarity of traditional 2D platforms while providing spatial awareness and immersion. Although prior work has prominently explored such HUIs in the context of mixed reality, we still lack a cohesive understanding of the unique design possibilities and challenges of such combinations, resulting in a fragmented research landscape. We conducted a systematic survey and present a taxonomy of HUIs that combine conventional display technology and mixed reality environments. Based on this, we discuss past and current challenges, the evolution of definitions, and prospective opportunities to tie together the past 30 years of research with our vision of future HUIs.**

***Index Terms*—Survey, cross-device interaction, hybrid user interfaces, augmented reality, mixed reality, cross-reality.**

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I. Introduction

IMMERSIVE augmented reality (AR) and virtual reality (VR) is gradually gaining relevance in everyday life, with affordable off-the-shelf hardware becoming increasingly available to consumers. These mixed reality (MR) platforms[1] have now evolved to the point where researchers can explore the nuances of interaction design without being constrained by major technological limitations. In this context, Feiner and Shamash [48] proposed in 1991 the concept of *hybrid user interfaces* (HUIs), which combine "*heterogeneous display and interaction device technologies.*" This concept theoretically allows for an infinite integration of technologies, yet, such heterogeneous combinations are especially compelling for MR environments: The ubiquity, convenience, and familiarity of conventional 2D platforms (e.g., smartphones, desktops) provide a perfect complement to the immersion and complexity of optical see-through (OST) and video see-through (VST) head-worn devices (HWDs) [2]. Yet, although the concept of HUIs has persisted for decades (see Fig. 1.), no coherent delineation has emerged. As a result, there is a distinct lack of consistent design models and terminologies—fragmenting the research community across overlapping research areas such as cross-reality systems [3], transitional interfaces [54], or cross-device interaction [16].

For example, the seminal cross-device taxonomy by Brudy et al. [16] provides an overarching model for the research

[1] In this work, mixed reality refers to both AR and VR (cf. [144]), as discussed in Section IV-C.

[2] We refer to "*head-worn devices*" (HWDs) instead of "*head-mounted displays*" (HMDs) to emphasize the increase in wearability and capabilities of current hardware, but intentionally kept the previous term HMD for describing older hardware.

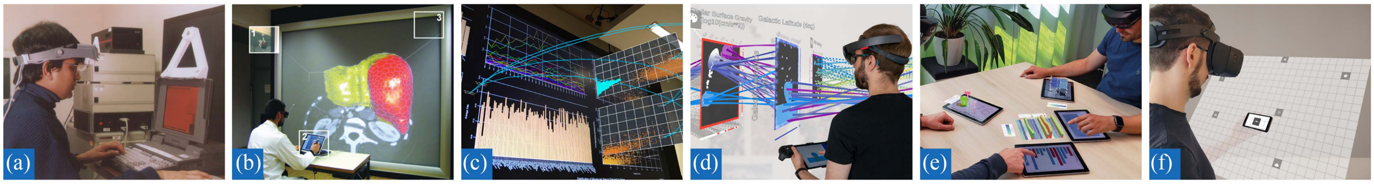

Fig. 1. We take a look at 30 years of hybrid user interface research and its evolution, focusing on combinations of conventional 2D devices with mixed reality environments. From left to right, (a) starting with its definition [48], (b) early extensions [13] (Image © IEEE 2006), and (c) current usage for augmenting displays [127] (Image © Reipschläger et al., CC BY 4.0), (d) extending tablets in single-user [68] (Image © Hubenschmid et al., CC BY 4.0) and (e) multi-user scenarios [91] (Image © Langner et al., CC BY 4.0), and (f) finally shifting towards more empirical studies [73] (Image © Hubenschmid et al., CC BY 4.0). All images used with permission. To explore our investigated corpus, please visit https://imldresden.github.io/huis.

area of HUIs. However, their taxonomy only considers established devices (e.g., mobile devices) and homogeneous combinations, leaving topics such as MR environments largely for future work. Yet, without firm design principles and in the face of countless possible device combinations, the design space of HUIs can appear bewilderingly large. Therefore, we extend the existing taxonomy by examining complementary cross-device interaction between traditional 2D device technologies and novel MR platforms as a prevalent subset of HUIs. By first examining this subset, we take a first step towards a better understanding of the broader research area of HUIs. Thus, we aim to establish a common terminology, allowing researchers and practitioners to better benefit from shared insights, establish a consistent framework, and inspire future systems. This would, in turn, enable the creation of a cohesive understanding of the unique design possibilities and challenges of HUIs.

Toward this goal, we examine the past, present, and future of HUIs, focusing on the unique combination of MR environments with conventional display technologies, thus integrating the research area of HUIs into the wider cross-device taxonomy. Overall, our work contributes:

- A **positioning of MR-HUIs**, creating a better understanding of the term within the current fragmented research landscape (Sections II and VII).
- A **systematic literature survey** (Section III) of HUIs that combine 2D devices and MR environments, from which we **present our own taxonomy** (Section IV) and **identify current trends** (Section V).
- A **discussion of the challenges and research opportunities** that describe how our investigated HUIs have evolved (Section VI), paving the way for their **future development and research** beyond current technological restrictions (Section VII).

II. What is a Hybrid User Interface?

Since 1991, the term "*hybrid user interface*" has continued to evolve. Despite significant advances in device technologies, no coherent definition has emerged that delineates HUIs from related research areas. This lack of common understanding makes it difficult to compare results and share insights. In the following, we first review prior definitions and the *background* (Section II-A) of HUIs, building on previous work by Satkowski and Méndez [133], and position HUIs in relation to current *adjacent research areas* (Section II-B). Based on this, we discuss how we can *identify* HUIs (Section II-C) and derive three *attributes* that specifically characterize HUIs that combine MR environments with conventional display technologies (Section II-D) to guide our literature survey.

A. Background

The term HUI was coined in the early 1990s by Feiner and Shamash, describing a combination of "*heterogeneous display and interaction device technologies*" [48]. They argue that physical device sizes decreased with the advent of portable computing devices (i.e., laptops). This led to reduced interface real estate while still retaining high-resolution input and output. In contrast, immersive technologies such as MR (especially HWDs)—back then and still mostly today—offer a lower resolution for both input and output space. However, AR has the potential for virtually unlimited interfaces that exceed the capabilities of conventional display technologies. Thus, they propose to combine these technologies by "*taking advantage of the strong points of each*" [48], treating the technologies as complementary instead of competing. They exemplify this concept in a "hybrid window manager", combining a high-resolution yet size-restricted desktop with a low-resolution yet virtually unlimited AR head-mounted display interface into a unified application that blurs the boundaries between interfaces.

This initially broad scope opened up a vast design space, but its ambiguity may have limited the adoption of the term within the field, leading to the diffusion of this term as it was applied to an increasing variety of device combinations over the years. Although one prominent theme was the combination of 2D devices and immersive MR environments, this was not universally shared by all prior works. On the one hand, Butz et al. highlighted that HUIs extend to various "*technologies and techniques, including virtual elements such as 3D widgets, and physical objects such as tracked displays and input devices*" [19]. They noted that the resulting global AR space can be shared, which is also discussed by Feiner, as HUIs combine all devices "*in a mobile, shared environment*" [46]. Bornik et al. further emphasize the potential combination of MR environments with conventional 2D display technology for HUIs, as they "*pair 3D perception and direct 3D interaction with 2D system control and precise 2D interaction*" [13]. This is echoed by Geiger et al., who state that HUIs "*combine 2D, 3D, and real object interaction and may use multiple input and output devices and different modalities*" [51]. In contrast, Strawhacker and Bers employ HUIs in a broader context without MR, presenting a HUI that

TABLE I
An Overview of Adjacent Research Areas and Their Relation to HUIs

Research Area	Description	Relation to HUIs
Distributed User Interfaces [39]	Foundation for all research on multi-device usage.	HUIs are one possible realization, focusing on distributing interfaces across heterogeneous devices.
Complementary Interfaces [163]	Symbiotic combinations of devices and interfaces through complementarity.	HUIs focus on complementarity between devices and thus are a technological approach to complementary interfaces.
Cross-Device Interaction [16]	Describes general research on homogeneous and heterogeneous device combinations.	HUIs are a subset of cross-device interaction focusing on heterogeneous combinations.
Cross-Reality Environments [3]	Systems and interfaces that span across different points on the reality-virtuality continuum.	Significant amounts of prior work in HUIs combine MR environments (e.g., AR and VR) with conventional displays (i.e., reality), thus representing a subset of cross-reality.
Transitional Interfaces [103]	Describes transitions between environments, interfaces, and devices.	HUIs may use transitional interfaces when switching between devices; likewise, transitional interfaces may encompass multiple heterogeneous devices to be switched between.

allows "*users [to] switch freely between tangible and graphical input*" [146]. One commonly shared theme is the importance of *complementarity:* For example, Sandor et al. state that "*information [in HUIs] can be spread over a variety of different, but complementary, displays*" [131]. Furthermore, in line with Butz et al. [19], they describe that users of HUIs can "*interact through a wide range of interaction devices*" [131]—we thus see the potential of HUIs not within a random assortment of technologies, but in a principled integration of different standalone "*interaction devices*".

B. Adjacent Research Areas

The combination of complementary device technologies opens up a vast design space with countless possible combinations. These device combinations are, however, not exclusive to HUIs. In this section, we describe the intersection between HUIs and adjacent research and clearly position HUIs within the current research landscape (see also Table I for an overview).

1) Distributed User Interfaces: Elmqvist [39] defines the term *distributed user interface* as an interface whose components are distributed across one or more dimensions, such as input, output, platform, space, and time. This theoretical perspective can be seen as the foundation of any research on multi-device usage, including multimodal interaction. For HUIs, all proposed dimensions are relevant, as they span multiple technologies and distribute the user interface accordingly. However, by combining heterogeneous technologies, HUIs aim to distribute input and output to the most suitable device to achieve a goal while focusing on their complementary use. Therefore, we see *distributed user interfaces* as an overarching conceptual model, with HUIs representing a possible technical realization of this concept that focuses on heterogeneous devices.

2) Complementary Interfaces: Recent works by Zagermann et al. [163] as well as Elmqvist [40] highlight that attributing unique roles, properties, and purposes to individual devices and modalities can lead to meaningful combinations of interfaces that support users in their current task at hand. Such *complementary interfaces* distribute interaction across devices and modalities to establish a "*symbiosis of interfaces, where each component purposefully increases the quality of interaction*" [163]. In the context of HUIs, complementary interfaces can be considered as an overarching concept that includes combinations of homogeneous and heterogeneous devices, but also input (e.g., interaction techniques) and output modalities (e.g., visually or auditory). The core ideas of complementary interfaces are typically part of HUIs, in that HUIs represent a technical realization of this concept.

3) Cross-Device Interaction: Brudy et al. [16] provide a comprehensive overview of the field of *cross-device interaction*. Here, the focus is on research that "*transcends the individual device and user*" [16], which unifies research that is focused on different kinds of multi-device environments, ranging from multi-monitor setups to ad-hoc mobile device ecologies. Although Brudy et al. [16] list head-worn MR devices and tangibles as part of their cross-device taxonomy, they do not further elaborate on combinations of heterogeneous (e.g., non-immersive and immersive) devices.

Therefore, cross-device interaction can be seen as an umbrella term that includes research not only on homogeneous but also heterogeneous combinations—the latter of which includes HUIs. Some of the research on homogeneous cross-device interaction (e.g., attention switching) can be transferred to HUIs. However, HUIs have unique challenges and opportunities, for example, with regard to heterogeneous roles of devices, conflicting interaction spaces, and co-dependencies of devices.

4) Cross-Reality Environments: Using the reality–virtuality (RV) continuum [105] as a foundation, the research area of *cross-reality environments* investigates the benefits of combining various points on the RV continuum. Key aspects of cross-reality environments include "*smooth transition[s] between systems using different degrees of virtuality*" and "*collaboration between users using different systems with different degrees of virtuality*" [142]. Recent taxonomies by Auda et al. [3] and Wang and Maurer [155] further solidify concepts such as transitioning between different points on the RV continuum or concurrently using multiple distinct systems along the RV continuum.

For a single user, such cross-reality environments typically create a sequence of actions (e.g., switching devices). Depending on the workflow, this could be described as a migratory interface [16], asynchronous HUI [72], or transitional interface [22], [103]. Furthermore, given that previous work often focuses on HUIs that combine 2D IO components with MR environments (e.g., [13], [19], [48], [51]), we see cross-reality as a potential umbrella term, where a subset of prior HUIs (see Section II-C) lies at the intersection between cross-reality and cross-device interaction: While cross-device interaction focuses on the combination of *devices*, the area of cross-reality concentrates on the combination of *realities*. Thus, the area of cross-reality research encompasses both homogeneous (e.g., collaboration between HWDs in different realities) and heterogeneous device combinations (e.g., switching from desktop to VR). We consider the latter as part of our HUI terminology.

5) Transitional Interfaces: The MagicBook by Billinghurst et al. [11] is often described as the first *transitional interface* [22], [103]: Here, a user can move seamlessly along the RV continuum—from browsing the physical book to a handheld AR display to immersive VR. Although they can be regarded as a subset of cross-reality, transitional interfaces specifically focus on the design of transitions and their effect on users [103]. While early head-mounted displays required a discrete switch of hardware to move across interfaces, currently available HWDs allow for continuous transitions by interactively adding or removing virtual contents.

Similarly to research on cross-reality environments, transitional interfaces typically involve a sequence of activities: A user solves one aspect of a given task in AR and continues to work on the activity in VR. The transition keeps the user oriented in the task space, choosing one manifestation of the RV continuum at a time. However, for HUIs, connecting to multiple manifestations at the same time is a key ability. In line with previous research, we "*think of HUIs and transitional interfaces as complementary*" [22], rather than competing: A HUI may use a transitional interface when switching between devices; likewise, a transitional interface may encompass multiple heterogeneous devices to be switched between.

6) Further Related Terms: Adjacent research areas additionally use related terms to describe their work: The term cross-device interaction is often used interchangeably with the term "cross-surface interaction", while earlier work in that area is often considered as "multi-device" or "multi-display" systems [16]. Similarly, there are other terms that are related to HUIs, but focus on interaction techniques (i.e., "hybrid interaction" [9], [85]) or the setting (i.e., "hybrid virtual environment" [22], [33], [153]). The term "augmented displays" was previously used to describe integral concepts of HUIs (cf. [126], [128]). Therefore, we consider it as a unique configuration for HUIs.

C. Characterizing Hybrid User Interfaces

Research on HUIs shares several common themes (e.g., *complementarity*, *heterogeneity*), yet the term remains technology-driven and potentially misunderstood: A large number of prior HUIs describe the term as a combination of 2D and 3D technology [13], [39], [63], including the initial system demonstration by Feiner and Shamash [48]. Moreover, the term HUI was previously also used for different constellations of IO components (e.g., desktop combined with tangibles [146], mobile devices [10], or conversational interfaces [97]), indicating wider applicability. For the purpose of our survey, we modernize the definition of HUIs by Feiner and Shamash [48] within the current research landscape:

> *Hybrid User Interfaces are an area of cross-device computing that leverages distinct benefits of heterogeneous components with input and output (IO components).*

In contrast to its initial definition, we explicitly concentrate on conceptual device capabilities instead of specific technologies to avoid being limited by current hardware capabilities, but are intentionally vague about possible device combinations (e.g., see cross-device interaction [16] for a potential ontology). To this end, we use the term *IO component* throughout this work to refer to a standalone device set with the input and output capabilities necessary for interacting with a given application (e.g., desktop with mouse and keyboard, VR HWD with controllers).

While this definition highlights the broad potential design space of HUIs, it also lacks specificity and, therefore, limits its utility for our survey: For example, a combination of tangibles and a desktop computer might be considered a HUI and likewise, a combination of an AR HWD with a tablet—increasing the blurriness of the research stream instead of increasing its focus. Therefore, to explore this vast design space and gain concrete insights into commonalities of HUIs, *we focus our work on the specific HUI subset combining 2D with MR-enabled IO components*. This combination captures our interest, as it was initially presented by Feiner and Shamash [48], is most prevalent in prior HUI literature [133], and also reflects on work presented at the IEEE ISMAR workshop on HUIs (2023) [69], constituting the most recent and comprehensive outlet for work on HUIs. We thereby explicitly exclude the vast research area of *tangible interaction* [77] or nascent research areas (e.g., brain–computer interfaces [28], Internet of Things [130]) from this subset, thereby increasing the specificity of our survey.

For the purpose of differentiating between the results of our survey and possible implications to the broader field of HUIs as well as to improve the readability of our paper, we will refer to this subset as *MR-HUI*.

D. Attributes of Mixed Reality Hybrid User Interfaces

We framed our work on the contemporary and most prevalent subset of HUIs: a combination of 2D IO components with MR environments. We derive three **attributes** based on previous usage of the term to further guide our literature review. Please note that the first two attributes are indicative of the broader area of HUIs, while the last attribute specifies the constraints of MR-HUIs.

Multiple IO components in heterogeneous roles: HUIs typically combine multiple IO components where each fulfills a need that is not adequately addressed by other components. Although each IO component is self-contained, a HUI is deliberately spread across multiple components to intentionally "*take advantage of the strong points of each*" [48]. We also see the potential beyond technological aspects and broaden our scope to include combinations of heterogeneous *roles*.

IO components are codependent: A HUI is composed of multiple IO components, but the real power does not emerge from any individual IO component, but from the interaction of all of them [157]. A HUI thus acts as one holistic application from the user's perspective. The deliberate spread of responsibilities across IO components requires a certain degree of co-dependency between IO components (i.e., a system may

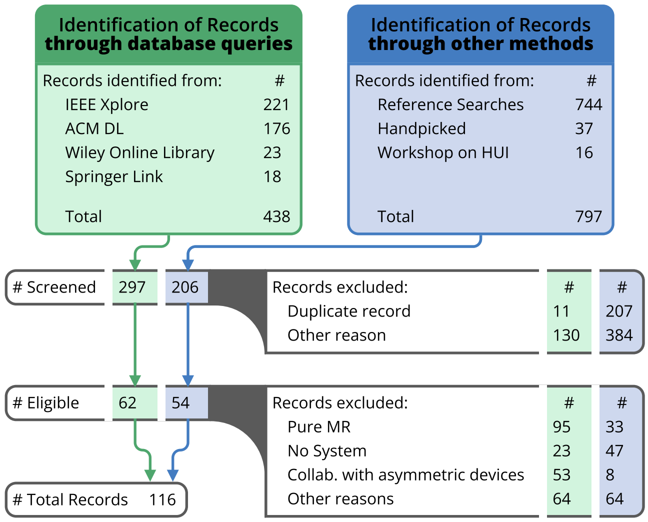

Fig. 2. Overview of our reviewing process including paper counts, following PRISMA. Records were rejected once a single exclusion criterium was fulfilled, yet, some records potentially fulfilled multiple criteria (e.g., survey papers [3]). The initial corpus of papers (n=1235) including all codes is part of the supplemental material of this submission.

become nonfunctional without all IO components present). We examine both synchronous (i.e., using IO components in parallel) and asynchronous usage (i.e., using IO components in sequence) [13], [72].

Complementing 2D with MR IO components: A common aspect found in prior HUI literature is to "*pair 3D perception and direct 3D interaction with 2D system control and precise 2D interaction*" [13]. Given the (at times) conflicting needs of 2D and 3D spaces, combining 2D and MR IO components can yield a superior result. For the remainder of this work, we refer to such IO components as either *2D IO component* or *MR IO component*.

III. Review Methodology

We look at research that matches our previously specified attributes to obtain corpus of MR-HUI publications. This section describes the process for identifying, filtering, and analyzing relevant publications, following the PRISMA [113] guidelines. We present the general search strategy (Section III-A), selection process (Section III-B), and data extraction (Section III-C). Moreover, the limitations of our procedure (Section III-D) and possible extensions of the survey (Section III-E) are highlighted. Finally, we describe how this survey can be used by other researchers and practitioners (Section III-F). The complete survey corpus, its coding, and the scripts used to prepare and analyze the data can be found in the supplementary material.

A. Search Strategy

In accordance with the PRISMA guidelines, we collected the papers using two different identification approaches (see Fig. 2), which we present in this section.

Identification via databases: Our survey focuses on publications that combine 2D IO components with MR environments. As the term "HUI" is not consistently used in previous work, we used adjacent terms and their synonyms (see Section II-B)

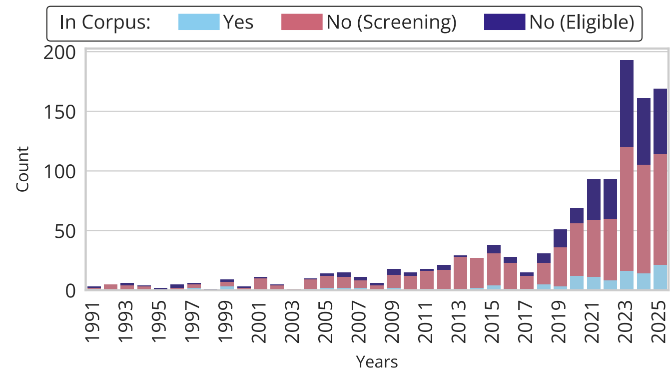

Fig. 3. Record distribution over the past three decades.

to build a query that captures a broader range of potential publications that present HUI applications.

We iteratively refined our keywords and evaluated them on a base corpus. Starting from the initial keyword "hybrid user interface", we identified synonyms used in the literature and extended our set of keywords. This resulted in three sets of keywords focused on different aspects that we aimed to capture. First, *Set A* includes keywords that could be used interchangeably with the term HUI. Next, *Set B* consists of adjacent terms and their synonyms that are not necessarily MR-specific. This is why, with *Set C*, we further narrow down the search to MR-related terms. The complete list of terms in each set is as follows:[3]

Set A: "Hybrid User Interface", "Complementary Interface", "Augmented Display", or "Cross-Reality"

Set B: "Hybrid Virtual Environment", "Hybrid Interaction", "Cross-Device", "Cross-Surface", "Multi-Device", "Multi-Display", "Distributed User Interface", or "Transitional Interface"

Set C: "Augmented Reality", "Virtual Reality", "Mixed Reality", or "Extended Reality"

The query was constructed using the expression: `+SetA or (Set B and Set C)+`. We focused on archival, peer-reviewed publications, including full and short papers in journals and conferences, as well as book chapters, workshop submissions, posters, and works in progress. We searched in common digital libraries for publications in Human–Computer Interaction and Visualization, namely IEEE Xplore, ACM Digital Library, Springer Link, and Wiley Online Library. The searches with the described query [4] in these libraries [5] resulted in 438 publications (see Fig. 2). The cut-off date for all searches was December 11th, 2025.

Identification via other methods: In addition to the query search—and in line with PRISMA guidelines—we selected papers through three other methods (see Fig. 2). First, we selected all papers referring to seminal works of adjacent research areas (i.e., [3], [16], [39], [103], [126], [163]) or to the original definition of HUIs [48], through a Google Scholar search using

[3]All terms were used in singular and plural, as well as with or without hyphens (where appropriate).

[4]The specific search syntax for each library can be found in the supplemental material.

[5]The advanced search of the Springer library only allows searching in the title and keywords and not in the abstract.

"Publish or Perish" [62]. Second, we manually added further publications that were part of the authors' paper collection, discussed among four authors, and eventually identified as potentially relevant. Some of these handpicked papers did not appear through other search strategies as their individual focus was not the technological setting but the investigated use case (e.g., studying window management of virtual displays [114]). Finally, we selected all publications presented at the IEEE ISMAR 2023 Workshop on Hybrid User Interfaces [69], as contributions to this workshop have explicitly been peer-reviewed in the context of HUIs. The three methods resulted in 797 publications (see Figs. 2 and 3). The cut-off date was December 11th, 2025.

B. Selection Process

After retrieving the initial corpus of papers (n = 1235), we preprocessed the different output formats and merged them into one table. Three authors screened the reviewed corpus and filtered out duplicates and papers unrelated to MR. In addition, workshop proposals, complete books, dissertations, or conference proceedings were also removed.

Subsequently, three authors checked the eligibility of the remaining publications (n = 503). For that, the following exclusion criteria (based on Section II-D) were defined:

- The publication is a duplicate (content-wise) of another (e.g., demonstration [121] of system [122]).
- No prototype or system was presented (e.g., discussion of opportunities and challenges [90], [123], [164], [167]).
- Only a technological basis is described (e.g., frameworks [66], [130]).
- The publication only presents a summary of systems already in our corpus (e.g., position papers [45], [46]).
- A pure MR system without other IO components is described (e.g., combining AR and VR environments [5], [26]).
- Other device capabilities are only used as input or output modality (i.e., IO components are not standalone, e.g., attaching input sensors to an AR HWD [32], [102]).
- The publication only presents a collaboration across asymmetric devices (e.g., one user on a 2D IO component, another in an MR environment [98], [110]).

During both selection steps, we split the data set between authors and discussed entries if the decision was unclear. This resulted in 116 relevant publications within our corpus.

C. Data Extraction

Since we see HUIs as a sub-category of cross-device interaction, we started with aspects defined by Brudy et al. [16] in their survey. This was extended with common HCI metadata, such as the contribution type [161] or the evaluation strategy [92]. Furthermore, we recorded each publication's challenges, future work, use case, and devices and terminology used. To validate the initial set of codes, we randomly selected 10 papers from our corpus that were coded by three authors. This allowed us to (1) verify if the categorization works, (2) add missing codes, and (3) establish a common ground between authors. With the categories finalized, four authors coded the remaining papers. To ensure the rigor and reliability of the analysis, we employed researcher triangulation: two authors independently coded all publications, and each paper in the final corpus was reviewed by at least two researchers. No author assessed the relevance of their own work. After each paper was coded, the same four authors discussed each publication and clarified conflicts in a coding meeting. They further clustered challenges, use cases, and terminology used throughout the corpus.

D. Limitations and Further Considerations

We rigorously designed and conducted our survey. However, we identified limitations that we present in this section.

Terminology Bias: HUIs can be described by a multitude of adjacent terms (see Section II-B), making it difficult to create a query that can capture all the systems within this field. Although we aimed to create the best possible query, this still led to a potentially incomplete set of publications. Therefore, we decided to add other sources (see Section III-A) to our survey corpus.

Strict Eligibility Criteria: We searched for a specific type of device combination (i.e., MR-enabling devices and conventional 2D displays), leading to strict eligibility criteria (see Section II-D). To avoid being overly restrictive, we decided to integrate papers that meet our characteristics but leave room for interpretation, especially system papers representing potential directions for future research. We discuss these edge cases and their implications in Section IV-C. We acknowledge that our corpus is not exhaustive with regard to possible HUI systems caused by the use of said criteria and our intentional focus on MR-HUI. Yet, we see our corpus as a representative and substantial set of research on MR-HUI, showcasing trends that can be generalized to the larger set of papers not captured by our query. Although no qualitative analysis can guarantee a single definitive taxonomy, we applied an overall methodology that strengthens the validity of our results and ensures that the resulting structure is both rigorous and comprehensive.

E. Dissemination and Extension

We have made our literature corpus available using the Indy Survey Tool [30] as a GitHub project that hosts an interactive website for users to explore and filter our survey results, as well as to submit other work to our corpus (see https://imldresden.github.io/huis).

F. How to Use The Following Survey

Our survey aims to reveal common patterns and identify shared dimensions within MR-HUIs. Our work can be helpful in three ways: (1) By **classifying past research**, our following *taxonomy of key characteristics* provides a general framework that can be used to describe and understand inherent properties of MR-HUIs. (2) By **identifying current trends**, our survey shows emerging trends in device combinations, use cases, contribution types, and evaluation strategies. Readers can understand *how* MR-HUIs are used, informing the design and evaluation of upcoming MR-HUIs. Finally, (3) our survey can **inspire future systems**, serving as a roadmap for the next generation of HUIs. Throughout our reporting (Sections IV and V), we denote the amount of literature in our corpus for each characteristic within a colored box mapped on a gradient with the total paper count (n=116) as the maximum value. Additionally, we provide a curated set of exemplary papers from our corpus for

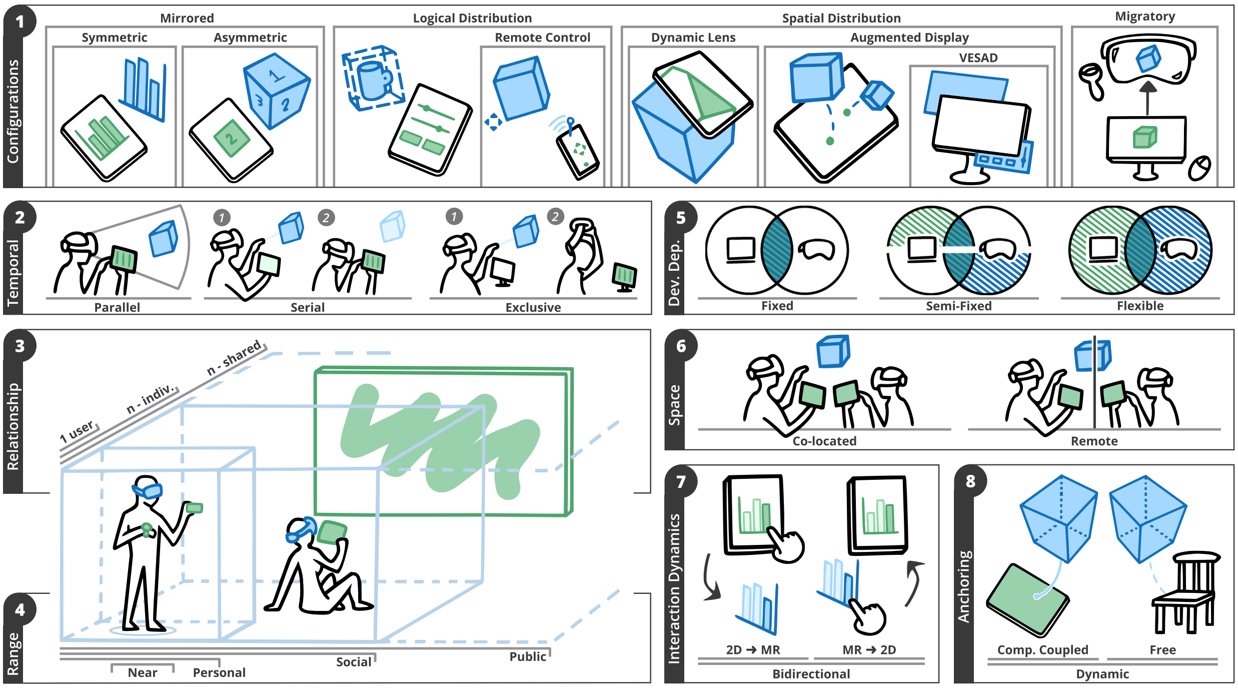

Fig. 4. We present a taxonomy of key characteristics for mixed reality hybrid user interfaces with eight dimensions: *configuration*, *temporal*, *relationship*, *range*, *device dependency*, *space*, *interaction dynamics*, and *anchoring*. IO components are highlighted in green for content on a 2D screen and blue for content in a mixed reality environment.

each characteristic, which can be used as a starting point for further reading. Since systems can be attributed to multiple characteristics, dimensions, or other categories, the sum of each category does not necessarily match the total number of records within our corpus.

IV. A Taxonomy of Mixed Reality Hybrid User Interfaces

Based on our survey, we establish a *taxonomy of key characteristics* for MR-HUIs (Section IV-A) that can characterize existing research and inform new research. In addition, we describe *emergent trends and opportunities* (Section IV-B) and highlight *edge cases* (Section IV-C) of our attributes characterizing MR-HUIs.

A. Taxonomy Dimensions

We adopt six cross-device characteristics of Brudy et al. [16] (*Dimensions 1–6*) and introduce two additional dimensions to better represent the design space of MR-HUIs. To reflect the nuances of MR-HUI, we extend and reframe each dimension and explain them accordingly. Although we describe these dimensions as discrete characteristics, they should be seen as continuous spectra, where systems, configurations, and interaction techniques can dynamically span multiple facets.

Dimension 1. Configuration*:* The configuration dimension describes how content and control are distributed across IO components for a single user. Although we based our configurations on the cross-device taxonomy (i.e., *mirrored*, *logical distribution*, *spatial distribution*, *migratory interfaces*), we identified six configurations unique to MR-HUIs, namely *asymmetrical mirrored*, *symmetrical mirrored*, *remote control*, *dynamic lens*, *augmented displays*, and *VESADs*.

Mirrored configurations duplicate content in different IO components. Given the perceptual differences of components in MR-HUIs, we distinguish between *symmetric mirror* and *asymmetric mirror* configurations.

- ▷ *Symmetric Mirror* 14 configurations duplicate content between IO components, with each IO component displaying the exact same view of information. This can reduce complexity when interacting with virtual content such as 3D sketching [2], [35] or immersive analytics [18], [68]. For example, a HUI can provide contextual connection based on users' surroundings in MR while providing familiar input on the 2D IO component.
- ▷ *Asymmetric Mirror* 15 configurations show the same view of information but make use of the additional perceptual dimensions offered by MR IO components: For example, this can be used to display a full 3D model or visualization in the MR environment, which is mirrored to an orthographic front view on the 2D IO component [76], [140], [149].

Logical Distribution 67 describes configurations where content and control are distributed according to each IO component's strength, usually involving a mutually exclusive allocation of responsibilities between IO components. Most systems in our corpus involve some kind of logical distribution, such as offloading text input [8], [56], [169]), shared and personal space [80], [129], or general application-control [108], [129], [132]) to 2D IO components, while the MR environment is used to display content in-situ.

▷ *Remote Control* 12 describes a stricter subset of *logical distribution*, where the 2D IO component provides an alternative (but not exclusive) control over content in the MR environment. This can be useful for providing direct interactions when close by and indirect interaction from farther away (e.g., during 3D sketching [35]) or providing a more ergonomic option [42].

Spatial Distribution describes configurations that deliberately spread content across different spatial locations in the continuous real-world space. Such a distribution can be achieved through different means, described as *dynamic lenses*, *augmented displays*, or *VESADs*. Here, the content is aligned to the 2D IO component (i.e., *augmented display*, *VESAD*) or reacts to the position of the 2D IO component (i.e., *dynamic lens*).

▷ *Dynamic Lens* 10 allows 2D IO components to act as a dynamic peephole [104] into a larger information space. While 2D IO components provide a constrained view, the MR environment is unrestricted and can use the real environment. This requires the 2D IO component to be spatially aware, enabling, for example, 3D slicing showing a cross-section of a 3D model on the 2D IO component [89], [101], [149].

▷ *Augmented Displays* 18 use the unrestricted visual output of an MR environment to extend a 2D IO component beyond its potential visual and interaction capabilities, acting as a 3D augmentation that is attached to the 2D IO component [27], [34], [91], [127]. This category was initially defined by Reipschläger et al. [126], [128] as "*seamless combination of high resolution touch and pen enabled displays with head-coupled Augmented Reality*".

▷ *VESADs* 19 ("*Virtually Extended Screen-Aligned Displays*") were initially defined by Normand and McGuffin [109] as a virtual AR screen "*that is centered on, and coplanar with, a smartphone*". The content is strictly aligned to a 2D IO component as a seamless display extension [48], [73], [91], representing a subset of *augmented displays*. For example, *VESADs* can be useful for offloading menu elements into MR to save screen real estate on a 2D IO component [15], [109], [128] or provide alternative interaction capabilities [15]. To better represent the diversity of real-world multi-display configurations, we also include configurations that are aligned to 2D IO components but not necessarily co-planar, such as extending 2D IO components with angled virtual 2D screens [114], [115], [125].

Migratory Interfaces 22 enable users to transfer their content or workflow from one device to another. Although originally considered asynchronous within the cross-device taxonomy [16], MR-HUIs can also utilize the MR environment to seamlessly transfer content between 2D IO components [141] or between a 2D and 3D IO component [1], [156], [158], [162]. In contrast, their asynchronous usage can take advantage of different environments to best support a holistic workflow (e.g., by switching between VR and desktop environment [24], [67]) while still behaving as one unified, continuous system.

Dimension 2. Temporal: Prior literature [13], [16], [72] classifies hybrid and cross-device systems as *synchronous* or *asynchronous*. Due to the diversity of IO components within MR-HUIs, we adopted the suggestion by Bornik et al. [13] to further differentiate between **parallel** and **serial** usage of IO components. Fully asynchronous usage of IO components was further classified as **exclusive** for cases where the usage of one IO component rules out the usage of another (e.g., due to spatial or time-related restrictions).

Some papers describe multiple interaction techniques that can be used, for example, in parallel or serial; others only present usages of one distinct aspect. We report the results accordingly: presenting the number of papers describing mixed and distinct temporal usage first and its subset describing only distinct usage second (e.g., 9 / 1).

Parallel 94 / 65 usage indicates that multiple IO components are used simultaneously, for example, when interacting with one IO component while observing the output on another IO component [27], transferring content across devices [68], or extending a 2D IO component in the MR environment [73], [91], [127].

Serial 45 / 9 usage indicates that multiple IO components are used one immediately after another, such as selecting objects of interest in the MR environment and then editing them on a 2D IO component [18]. Here, users have immediate access to all IO components but can focus on only one IO component at a time to reduce information overload or divide responsibilities between 2D and 3D interaction [13], [35], [47].

Exclusive 17 / 5 usage describes asynchronous systems where different IO components cannot be used simultaneously as part of one workflow but have to be used in sequence. This can be useful to bridge the gap between traditional 2D computing environments and VR environments [24], [67], [138].

Dimension 3. Relationship: The *relationship* category denotes the relation between users within one or multiple systems. The vast majority of our corpus describes **single-user** systems 103 : One user interacts with multiple complementary IO components (see Fig. 4 *1 user*). However, we identified several collaborative systems. We abstracted these into **multi-user with individual IO components** 9 : Each collaborator has their own set of IO components [129], [138] (see Fig. 4 *n-indiv.*); and **multi-user with shared IO component** 14 : A display is shared between collaborators as a public space [18], [89], [106], [127] (see Fig. 4 *n-shared*).

Dimension 4. Range: We examined the range of interaction across components as defined in the cross-device taxonomy [16]. Since the MR IO component is commonly worn on the user's head (e.g., AR HWD) or close to their body (e.g., handheld AR), we use this dimension to describe the scale of the 2D IO component relative to the user. In addition, the *relationship* can be an indicator of the *range* between IO components (e.g., *multi-user* can indicate *social* or *public* range). We differentiate between **near** 8 (i.e., IO component is close to the user's body, e.g., smartwatch [42], [55], [153]), **personal** 92 (i.e., IO component is in the personal space, e.g., smartphone or tablet [68], [89], [91], [132]), **social** 31 (i.e., IO component is in a social space accessible to collaborators, e.g., shared display [18], [106], [127]), and **public** 2 scale (i.e., IO component can be seen and interacted with by arbitrary bystanders).

Dimension 5. Device Dependency: With this dimension, we describe the autonomy of each IO component within the overall device ecology. We coded this as **flexible**, **semi-fixed**, and **fixed**:

Flexible 25 device dependency indicates that all IO components provide basic features—a single IO component could suffice to interact with a system in a meaningful way. This can be helpful for workflows that can be easily divided properly into specific subtasks for different environments, such as data analysis workflows [67], note taking [162], or sketching [2]. The main value of HUIs in this situation comes from the interaction between the components, such as the seamless transition between components.

Semi-Fixed 52 device dependency represents systems in which one IO component is completely independent, while others provide supplementary functionality and are thus reliant on the "main" component. This dynamic has been used primarily to extend the capabilities of existing 2D components, such as increasing the available screen space [48], [73], [91] or offering complementary views on existing content [8], [55], [127]. In contrast, a *semi-fixed* dependency can also be used to provide complementary capabilities to MR environments, such as providing a shared public space [80] or extracting content from 2D IO components [139].

Fixed 41 device dependency describes systems that can only be used meaningfully with all relevant components present. Here, responsibilities are exclusively distributed between components, such as using the 2D IO component as a haptic surface for touch [14], [18], [27], for contextual interaction within the MR environment [47], [68], [134] or as a spatially-aware controller [89], [101].

Dimension 6. Space: The space dimension describes whether IO components are **co-located** 116 (i.e., within the same physical space) or **remote** 0. Since it may be difficult to achieve a synchronous MR-HUI with remote IO components, all the records we surveyed were exclusively *co-located*. An asynchronous MR-HUI with *remote* IO components may be feasible but would likely forfeit potential benefits gained from any combination of complementary devices (cf. [16]). Instead, we see the potential of such remote combinations in collaborative scenarios with *multiple user having individual IO components* relationships. Potential remote collaboration scenarios might include individual MR-HUIs per location and user (e.g., a HWD to visualize data in AR and a handheld device for precise input): Here, the AR visualization could be shared and synced, while the handheld devices allow individual manipulations. However, such scenarios might also require user representations (e.g., to create awareness), a communication channel, and a merge policy for conflicting input. We also discuss opportunities for collaboration using MR-HUIs in Section VI-F.

Dimension 7. Interaction Dynamics: Since systems in our corpus are intentionally spread across multiple IO components, the interaction dynamics describe how each IO component can interact with a system. Building on the BISHARE [169] design space, which classified interaction concepts as either *HWD-centric* or *phone-centric*, we identified three kinds of dynamics:

Unidirectional (2D-centric) 51 dynamics, which signifies that input is only possible from the 2D IO component. Examples include touch input [18], [68], [91], mouse & keyboard input [48], [84], [115], or using 2D IO component as spatial controller [89], [101] (see Fig. 4 *2D → MR*).

Unidirectional (MR-centric) 7 indicates that it is only possible to use input modalities provided by the MR environment, such as controller [75], [95], [139] or mid-air gestures [80] (see Fig. 4 *MR→2D*).

Bidirectional 60 dynamics indicate that all IO components can interact with the system equally, for example, by switching between 2D and 3D sketching [35], visualizations [108], or transferring content [141], [162].

Furthermore, we tagged every IO component by interaction paradigms that they showcase. For this, we used the non-orthogonal tags: **symbolic** (WIMP) [160], **reality-based-interaction** (RBI) [79], **direct** (pointing at or touching objects to interact), and **indirect** (interaction target is offset from the location where the input is sensed) [116]. With a few exceptions (e.g., fixed study conditions, software toolkits), tracked HWDs and touch-enabled surfaces were tagged with RBI (85 and 59), e.g., because of pan/zoom through head/body movement and touch. We consider mid-air gestures (e.g., grab), pointing, touch, and gaze interaction as direct interaction, while the use of controllers with physical buttons, voice commands, and sign gestures (e.g., thumbs-up) are indirect interaction. Naturally, laptops and desktop computers almost exclusively relied on WIMP and indirect interaction through mouse/pointers and trackpads (42 in both cases), with a few exceptional peripheral devices. This analysis, however, did not reveal unexpected insights about, for example, underutilized IO component capabilities. Regardless, we forward the curious reader to our supplementary material for all details.

Dimension 8. Anchoring: This dimension describes where the content is placed in the MR environment. We extended the design space by Reichherzer et al. [122], which categorizes content as either world-fixed or device-fixed. In addition, previous taxonomies have explored anchoring in more detail (e.g., semantic and spatial coupling in world-fixed content [38], content layout of device-fixed content [23], [119]), which we consider out of scope for this work. Our corpus is split almost equally between three general anchoring techniques:

Component-coupled 32 anchoring relates content within the MR environment to the 2D IO components (*device-fixed* [122]). To create the illusion of spatial awareness and proper alignment of 2D IO components, *component-coupled* usually involves spatial calibration of the 2D IO component for stationary devices or active tracking for mobile platforms. *Augmented displays* and *VESADs* always involve a *component-coupled* anchor, while other systems require knowledge about the 2D IO component for transferring content [139].

Free 52 anchoring describes MR content that is independently placed in the world or attached to real objects in the environment (*world-fixed* [122]). This method can be used when the 2D IO component is not directly related to the MR environment, for example, when providing a menu in the 2D

Configurations	Temporal			Relation.			Range				Dev. Dep.			Space		Int. Dyn.			Anchoring			
	Parallel	Serial	Exclusive	Single	Multi - Individual	Multi - Shared	Near	Personal	Social	Public	Fixed	Semi-Fixed	Flexible	Co-Located	Remote	2D → MR	MR → 2D	Bidirectional	Comp. Coupled	Free	Dynamic	Total
Symmetric Mirror	14	9	1	10	3	4	1	9	6	2	4	10	2	14	0	10	0	5	3	7	6	14
Asymmetric Mirror	11	6	3	14	1	2	1	12	5	1	3	6	8	15	0	5	1	10	3	10	4	15
Logical Distribution	53	32	11	57	6	10	6	54	18	1	29	25	15	67	0	28	3	37	10	38	21	67
Remote Control	12	8	1	12	1	1	4	11	1	1	3	7	4	12	0	4	1	8	1	9	4	12
Dynamic Lens	10	2	0	10	1	2	2	8	3	1	8	3	1	10	0	7	0	4	5	2	5	10
Augmented Display	17	5	0	15	2	6	1	12	9	1	6	12	2	18	0	12	0	7	13	1	6	18
VESAD	19	3	0	18	2	3	3	15	4	1	4	16	1	19	0	16	0	4	12	1	8	19
Migratory Interface	13	12	9	21	1	2	2	20	6	1	6	6	12	22	0	1	3	20	2	10	12	22
(total)	94	45	17	103	9	14	8	92	31	2	41	52	25	116	0	51	7	60	32	52	34	

Fig. 5. The co-occurrences of codes between the *configuration* dimension across the dimensions *temporal*, *relationship*, *range*, *device dependency*, *space*, *interaction dynamics*, *anchoring*. Each row is shaded to show the frequency of dimension values for each *configuration*.

IO component [35], [152] or a simplified but detached view of the MR content [14], [108].

Dynamic 34 anchoring may support both *component-coupled* and *free* anchoring. Previous work has explored this approach in terms of transferring content from a 2D IO component to the MR environment or vice versa [68], [162], [169] or for cutting through 3D models [89], [101].

B. Emergent Trends and Opportunities

To discover possible usage patterns of different configurations, we look at the distribution and trends of *dimensions 2–8* across the *configuration* dimension (see Fig. 5). Although existing literature covers a wide range of possibilities, we can identify several trends: (1) *Spatial distribution* configurations (including *augmented display* and *VESADs*) have specific requirements, making them unsuitable for *serial* and *exclusive* temporal usage as well as *flexible* dynamics usage. Their focus on extending a 2D IO component is indicated by the lack of systems that demonstrate *unidirectional (MR-centric)* interaction dynamics and *free* anchoring. (2) *Migratory* configurations can be used regardless of their *temporal* dimension, but have only been explored so far within *single-user* systems. In this configuration, all IO components appear to be equally important for interaction, since almost every system in our corpus uses a *bidirectional* interaction dynamics. (3) *Unidirectional (MR-centric)* interaction dynamics is only used in configurations that make use of the extended 3D capabilities of the MR IO component (i.e., *asymmetrical mirror*, *logical distribution*, and *migratory interface*). (4) Although early work focused mainly on exploring complementary combinations in general *logical distributions*, the increase in hardware sophistication is reflected in an increase in configuration diversity: For example, *symmetric* configurations only appeared around 2016, while *remote control* configurations appeared around 2020. Since HUIs address an ever-shifting window of opportunity of contemporary hardware capabilities, the choice of possibilities is determined by the available hardware. We expect that new hardware will lead to novel combinations, creating new HUI *configurations*.

We can identify several research opportunities by looking at gaps in current usage: (1) MR-HUIs have been exclusively explored in *co-located* spaces. Although this can be partially attributed to the focus on *single-user* systems, several systems already demonstrate the potential of MR-HUIs for collaboration. Similarly, we can see a lack of systems within *public* range. In both cases, future research could explore the distinct roles of each IO component in these settings (e.g., territoriality, establishing shared and private spaces). (2) Only few systems have explored how to interact with 2D IO components using the MR IO component (*MR-centric interaction dynamic*). We see the potential in either *public* scenarios (e.g., avoiding hygienic issues) or dynamically enabling remote interaction with 2D IO components [64]: Here, a *symmetric* configuration may be useful to offer complementary interaction possibilities. (3) We attribute the lack of systems with *near* range to current MR hardware limitations. For example, the limited field of view makes it hard to augment smartwatches. However, *near* devices could provide a complementary interface to MR HWDs by providing at-a-glance information (cf. [12]) or touch interaction. (4) Since the *logical distribution* configuration represents a substantial amount of records in our survey, we see potential to further differentiate this configuration. Although such a fine-grained analysis exceeds the scope of this work, future MR-HUIs might help to reveal additional patterns.

C. Edge Cases

We discovered edge cases that were not unambiguously covered by our exclusion criteria (see Section II-D). We categorize these edge cases into three themes, discuss how they fit into our taxonomy, and sketch potential future directions.

Collaboration with asymmetric devices: One of our exclusion criteria (see Section III-B) was a collaboration with asymmetric devices (i.e., applications where users can interact only with one device in total). However, such systems can be situated within the cross-device taxonomy [16] and even be classified as "*hybrid*", with one user on a tablet and one in AR [53], [98], [110]. We believe that many of our *key characteristics* are not applicable to such systems. Although collaborative systems with asymmetric devices might still provide valuable insights for MR-HUIs, we argue that this would dilute our current focus on cross-device (as opposed to "*cross-user*") interaction. Instead, we see them as part of the research field of cross-reality environments (see Section II-B).

Reproducing reality & virtual reality: To avoid limiting our survey to currently available technologies, we also considered systems that simulate or reproduce reality, such as VST HWDs. Such device combinations are commonly used to overcome the limitations of current OST AR HWDs (e.g., increased field of view [109], avoiding different focal planes [56], [159]), evaluate systems in scenarios that are difficult to reproduce in reality [81] (e.g., supermarkets [37]), or even simulate hardware capabilities that were not feasible at the time of publication (e.g., (transparent) tablets [89], [149]). Although this can negate some of the benefits of HUIs (e.g., high-resolution displays of current mobile devices are limited by the clarity of VST HWDs), their conceptual application design contains valuable insights for the complementary use of IO components, regardless of the technology used. By extension, we consider combinations that employ a VR environment if they demonstrate complementary use of IO components according to our *attributes*, such as using a tablet in VR [35], [147]. In contrast, we excluded papers that did not fulfill our *attributes*, such as ones that do not establish a mutual dependency between the virtual environment and the simulated device [37].

Tangible interaction without visual output: Mobile devices combined with AR HWDs have potential for tangible interaction techniques that do not necessarily rely on the device's visual output [145]. This can be useful to extend the interaction design space. However, as they do not fulfill our *attributes* (i.e., standalone 2D IO component), we excluded records that do not rely on the mobile device's screen. We see such systems in another subset of HUIs, at the intersection of the broader field of HUIs and *tangible interaction* [78], which map digital interactions to real-world objects.

V. How Are Mixed Reality HUIs Used?

In this section, we take a closer look at how MR-HUIs are used throughout our literature corpus. We highlight findings of our corpus in terms of previously used *terminology* (Section V-A), *use cases* (Section V-B), *devices and combinations* (Section V-C), *contribution types* (Section V-D), and *evaluation strategies* (Section V-E). Finally, we provide a *summary of insights* (Section V-F) and discuss the *potential and pitfalls of HUIs* (Section V-G).

A. Terminology

We extracted the terminology used by each publication to better understand the terms used to describe MR-HUIs. Overall, we found that the author's terminology touched the following areas: **Hybrid User Interface** 29, referring to the term introduced by Feiner and Shamash [48]; **Hybrid** ⟨*other*⟩ 20, referring to areas such as hybrid computing environment, hybrid display system, or hybrid setup; **Cross-Device** 26 and **Cross-Reality Interaction** 14, relating to the adjacent research areas; **Multi-Device Interaction** 10, describing a setup related to cross-device interaction; **Augmented Displays** 4, predominately used by Reipschläger et al. [126]; **Transitional User Interface** 4, used in relation to cross-reality collaboration or HUIs. In addition, several records used a variety of **other terms** 13, such as *compound environment*, *display combination*, or *multimodal interaction*. Lastly, the rest had **no explicit terminology** 20.

B. Use Cases

We analyzed usage scenarios as described by the papers in our corpus and further clustered them into common use cases. The most prominent use case was **visual analytics** 33, ranging from abstract visualization for immersive analytics [25] (e.g., [18], [27], [68], [91], [127], [132]), dashboards [152], user study analysis [67], [108], and scientific visualizations [1], [13], [101]. This is unsurprising, since concepts such as multiple-coordinated views are widely established and lend themselves well to configurations such as the *asymmetric mirror*. This partially overlaps with the **medical** 7 domain, which uses HUIs for 3D examination [1], [13], [101] and surgery [75]. Another popular use case is **3D modeling** 13 [125], [126], [147], including 3D sketching [2], [35]. Several records present the area of **development and authoring** 13, including development toolkits [52], [108], [122] or programming-related tasks [8], [100], [128], [153]. We attribute several records to general **productivity** 16 tools, such as window management [48], extending desktop configurations [84], [114], [115], file transfer [141], note-taking [117], or general user interface improvements [15], [82], [85]. We also found several records in domains such as **gaming** 5 [106], [151], **entertainment** 6 (e.g., music [41], [87], television [4], [83]), **collaboration** 6 [19], [50], [129], [138], or **text entry** 6 [7], [56], [89]. Lastly, the remainder had **study-specific** 21 or **other** 19 use cases.

C. Devices and Combinations

As publications in our corpus combine multiple IO components (i.e., devices) in a complementary way, we recorded device technologies and their most common combinations (see Fig. 6). For records that did not have specific terminology to describe their hardware (e.g., [149]), we used current terms based on the dimensions of the device.

In terms of MR IO components, **AR HWDs** 87 were the most common device technologies, with a large part of systems using **OST AR HWDs** 69 and others using **VST AR HWDs** 22. For **handheld AR** 14, we differentiate between **handheld AR on smartphones** 8 and **handheld AR on tablets** 8. Other types of AR systems were less common, such as **projector-based spatial AR** 5, **stereoscopic projections** 2, and **CAVEs** 3. Lastly, since we also included VR environments, our corpus contained systems with **VR HWDs** 22.

For 2D IO components, we observed a similar spread between available device technologies: Several systems used mobile platforms 66 such as **smartwatches** 8, **smartphones** 33, **tablets** 29, and **laptops** 9. Stationary IO components 59 were almost as common, including **desktops** 37, **projectors** 6, **large displays** 9 (e.g., wall-displays), and **tabletops** 10.

		1991	1997	1999	2004	2005	2006	2007	2009	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	
MR-enabling Comp.	AR OST HWD	1	2	2	0	2	0	2	0	0	0	0	0	2	0	1	4	1	7	10	6	9	10	10	69
	AR VST HWD	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2	0	0	6	4	7	21
	VR HWD	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	1	2	4	1	2	1	4	4	22
	Smartphone	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	1	0	2	0	0	1	1	0	8
	Tablet	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	3	2	1	8
2D Components	Tablet	0	1	2	0	0	2	0	0	0	0	0	1	3	1	0	1	1	5	3	3	0	2	4	29
	Smartphone	0	0	0	0	0	0	0	0	0	0	1	0	3	0	0	0	0	5	7	0	6	7	4	33
	Desktop	1	1	2	0	2	0	0	1	0	1	0	0	1	0	0	1	1	2	1	4	3	6	10	37
	Tabletop	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	3	1	1	0	1	0	0	1	10

MR-enabling Components	2D Components: Tablet	Smartphone	Smartwatch	Desktop	Laptop	Projection	Large Display	Tabletop	
AR OST HWD	18	24	4	20	6	3	6	8	69
AR VST HWD	4	5	5	7	2	0	2	2	21
VR HWD	7	7	2	8	2	1	0	1	22
Smartphone	3	3	1	0	2	0	0	1	8
Tablet	2	1	1	1	2	0	2	0	8
Spatial AR	0	0	0	1	2	3	0	0	5
Stereo. Projection	2	0	0	0	0	0	0	0	2
CAVE	1	0	0	2	0	0	0	0	3
	29	33	8	37	9	6	9	10	

Fig. 6. (Left) Distribution of used device types for each year within our literature corpus (years without records were omitted). Here, the complete table is shaded based on the maximum value (i.e., 10) found in it. (Right) Amount of device combinations within our corpus across a selected set of MR and 2D IO components. Each row is shaded to show the frequency of 2D and MR component combinations.

Looking at the device combinations (see Fig. 6 left) over the years reveals an increase in device variation as more new form factors become available. This proliferation resulted in a variety of device combinations (see Fig. 6 right), with a focus on HWDs, although other MR devices were also used. Most often, 2D IO components were represented by handheld devices (e.g., smartphones), or desktop IO components. The usage of **AR OST HWDs** was preferred for the described 2D IO components.

D. Contribution Types

We classified papers in our corpus following the definition of Wobbrock and Kientz [161]. As some papers provide more than one contribution (e.g., an artifact that was used as an apparatus in an empirical user study), we distinguish between primary and secondary contributions and report the results accordingly (i.e., 15 / 4).

Artifact 73 / 11 contributions manifest new knowledge in a design-driven approach creating new systems, tools, and techniques. See Section V-C for further descriptions of, for example, device combinations used to create artifacts.

Empirical 36 / 19 contributions provide new knowledge in an evaluation-driven approach based on user studies. See also Section V-E for descriptions of evaluation strategies.

Theory 6 / 6 contributions improve existing concepts, creating frameworks. We consider thorough descriptions of design spaces as theoretical contributions.

Method 1 / 1 contributions create new knowledge that informs how researchers carry out their work.

Dataset 1 / 0 contributions offer a curated corpus for a specific topic to help design future MR-HUIs and layouts.

Two papers in our corpus [91], [169] are each categorized with a single primary contribution and two equivalent secondary contributions: Both present a design space as their main contribution (theory), followed by a system (artifact) used as the apparatus of a user study (empirical).

No papers were classified as surveys or opinion contributions. This is not surprising, as we focused on actual systems, which resulted in most artifact and empirical contributions. Similarly, some of the papers that could fulfill the criteria of other types of contribution were not considered, as they typically did not meet the eligibility criteria of our survey. Five papers contributed a theoretical contribution (i.e., a design space [91], [169]), showing that design spaces can be a way of exploring this nascent research area without necessarily implementing a system or study apparatus.

E. Evaluation Strategies

For papers that provided a primary or secondary empirical contribution, we coded their evaluation strategies [92]. Most papers featured one empirical contribution; others combined multiple user studies with different strategies.

The most common evaluation strategies within our corpus were empirical user studies that examine how users interact with a system 73 . In their cross-device taxonomy, Brudy et al. [16] further split this evaluation strategy into *qualitative and quantitative usage* and *informative (observational and elicitation)* evaluations: While **usage** 59 focuses on the usability and usefulness of the system and how it is appropriated [16], **informative** 23 evaluations involve studies that precede and inform the development of a system, involving users in the design process [16]. **Demonstrations** 21 are used to describe how systems are employed in an actual use case scenario but do not necessarily involve a real system implementation. In contrast, **technical performance** 5 evaluations (cf. *technical evaluation* [16]) focus on benchmarking an implemented system in terms of its technical capabilities. Lastly, several systems did not include any kind of evaluation 21 . Similarly, we did not observe any kind of **heuristics** 0 evaluation (i.e., using guidelines to analyze usability), which could be attributed to the lack of appropriate guidelines for MR-HUIs.

F. Summary of Insights

We present four main insights from our literature survey.

Term Fragmentation: Our corpus shows that terminology in prior research mostly favors the broader term *cross-device interaction* 65 over *hybrid user interfaces* 29 , while the emergent area of *cross-reality* 14 is gaining traction. A large number of eligible records in this survey were found in other research areas, barely mentioning such *hybrid* device combinations and thus making it difficult to search for and identify relevant prior work. This fragmentation is also reflected in their specificity, ranging from rather broad (e.g., *cross-device interaction* 26, *multi-device interaction* 10) to very narrow (e.g., *hybrid ⟨other⟩* 20) descriptions. While broad terms encapsulate a breadth of unrelated systems, overly specific denominators may lead to fragmentation and could impede the understanding of the field.

A similar fragmentation can be seen in the use of terminology to describe design dimensions. Although the cross-device taxonomy [16] provides an appropriate framework, we adapted many dimensions to better capture the unique design dimensions of MR-HUIs. Many useful terms that apply to MR-HUIs are hidden within artifact contributions (e.g., anchoring [122], dependency [169], configurations such as augmented display [126], [128], and VESADs [109]).

Parallel usage is predominant: We found that *parallel* usage of multiple IO components is by far the most predominant design choice. We think the reasons are twofold. (1) *Parallel* usage offers greater design possibilities. In contrast, *exclusive* (and to some extent *serial*) usage considers one IO component at a time, thus limiting the design potential. (2) As the time between using different IO components *exclusively* increases, it becomes harder to see the whole system as one coherent interface—and harder to classify. Systems with *exclusive* usage might be better described as *cross-reality*, which is concerned with the general usage of multiple systems in different "*realities*".

Optical see-through is the prevalent hardware choice, despite its drawbacks: AR HWDs 87 were the most common MR IO component. Although current VST HWDs 22 offer a wider field of view for digital content [109], the use of OST HWDs 69 was much more prevalent. We attribute this to (1) the unrestricted real-world field of view of OST HWDs greatly facilitating interaction with 2D IO components; (2) using OST HWDs further emphasizes the complementary nature of HUIs, as the addition of a secondary IO component offsets the drawbacks of the AR HWD; and (3) VST HWDs having only recently matured enough to be used in conjunction with other devices (e.g., in terms of text legibility due to limited pass-through resolution). We also observed a steady increase in empirical contributions over the past years, indicating that the hardware is now mature enough to conduct studies that are not confounded by hardware restrictions.

Lack of collaborative systems: Our corpus shows a distinct lack of multi-user systems 21, especially within public spaces 2. Although there is a great deal of work in the field of computer-supported cooperative work (CSCW) for collaboration across asymmetric devices—which we intentionally excluded from our survey—we see great potential in the use of MR-HUIs in collaborative scenarios.

G. Potential and Pitfalls of MR-HUIs

MR-HUIs are an intentional combination of off-the-shelf devices that would otherwise be used on their own. This is one of their strengths: Instead of requiring bespoke hardware tailored to a narrow range of tasks (e.g., tangibles), MR-HUIs leverage the user's existing device ecology. However, this can also have several pitfalls: Users' preferences for modalities might not necessarily reflect the design of the MR-HUI, as they might, for example, favor efficiency over effectiveness (cf. [165]). In addition, as off-the-shelf devices are designed for general-purpose use, they inevitably involve trade-offs. For example, a smartphone's screen may remain mostly unused inside MR environments, as users focus their visual attention on the content of the MR HWD. Should we favor specialized technologies, such as bespoke input devices, over general-purpose ones?

While specialized technologies may offer better performance for their intended use case, they lack the versatility to be used outside of their designated environments, leaving users with a plethora of single-purpose devices. In contrast, MR-HUIs leverage devices that are already within the user's ecology, connecting not only hardware capabilities but also software ecosystems. This could increase the adoption of immersive technologies, as they can be integrated to enhance current workflows and practices, rather than supersede them. Even outside of the context of MR-HUIs, these devices remain valuable, as smartphones and MR HWDs, for example, can still be used on their own.

MR-HUIs thus represent a pragmatic design solution that leverages the complementarity of currently available device technologies within existing device ecologies. Even as hardware limitations become less relevant due to increasingly sophisticated MR HWDs, MR-HUIs can inform the design of future interaction techniques and configurations. For example, recent advances in MR HWDs may render migratory configurations obsolete, as users can simply simulate a desktop in MR. Yet, using MR-HUIs, we can already investigate potential techniques and devices (e.g., hybrid input devices [70], [71]) that transcend the use of MR-HUI.

VI. Key Challenges and Research Agenda

Our thorough literature survey and our own experiences allow us to discuss key challenges and research opportunities.

A. Transitioning Between IO components

HUIs draw their strength from the combination of complementary IO components. While this can be beneficial, it also introduces several challenges concerning *visual attention switching*, *transferring content between IO components*, and *perceptual content synchronization*.

Visual attention switching: Introducing multiple visual output components divides the user's attention among each component, increasing mental load [118]. Prior work has investigated such visual attention switches in multi-display environments [119] and proposed metrics to potentially reduce strain. Although MR-HUIs can benefit from these insights, their design space is much broader in terms of display layout, enabling display layouts that are unbound by reality. Still, factors such as distance [6] or current hardware limitations have to be considered, as several works [36], [55], [109], [159] opt for VST AR HWDs to avoid differences in focal planes, which can further increase mental load [36]. Overall, more research is required to investigate potential effects and solutions for different display layouts [86].

Transferring content between IO components: MR-HUIs mix 2D and 3D content to make use of each IO component's strengths. While the distribution is often static (e.g., determined by the designer of the system), several systems have demonstrated the utility of transferring content from a 2D IO component to the MR environment [1], [139], [156], [162]. Specifically, prior work [139] highlights the importance of animations and linking when "pulling" content from a 2D IO component into an MR environment (cf. showing Bézier curves to selected MR content [68], [152]). Furthermore, recent research in the area of immersive analytics investigated visualization transformations between 2D and 3D [93], [94]. Several transition metaphors have been explored [162], [168] and compared [29], [120] in prior work, but further investigations are necessary to standardize these techniques.

Perceptual synchronization: Another challenge is found within the mapping and synchronization of content and interaction across components. While prior research has shown that an asymmetry of interaction (e.g., decoupling spatial interaction [140]) or information (e.g., showing simplified 2D views of 3D content [74], [76]) can be beneficial, this may come at an increased cost of user perception: For example, how does a 2D interaction affect its 3D equivalent, and how can we communicate this asymmetry?

Aside from these conceptual challenges in establishing a consistent mental model, we also have to consider technological challenges. In this context, prior work found that cross-device interaction techniques can be highly sensitive to network latency [96]. This sensitivity may be even more pronounced in MR-HUIs, especially if they appear as one conceptual device (e.g., the virtual screen in a *VESAD* configuration may lag behind the real screen). Here, more research is necessary to investigate how inevitable technological factors (e.g., latency) can confound findings.

B. Unchaining Device Capabilities

The past decade has seen a surge in both device variety (e.g., smartwatches, smartrings) and device capabilities (e.g., inside-out spatial tracking), which can also be seen in the increase in IO component combinations. Yet, 2D IO components such as smartphones are restricted by their form factor, favoring device ergonomics and portability but limiting their potential output capabilities. By combining them with MR IO components (e.g., AR HWDs), we can "unchain" their capabilities, enabling entirely new interaction possibilities (e.g., offloading menu items [15], [109], [125]), thereby inching closer to a form of "universal interaction" [86] and ultimately, Weiser's vision of ubiquitous computing [157]. While this can further expand the design space, we also recognize the need to establish guidelines to better understand the trade-offs and potential of each device (cf. [154]).

C. Evaluation, Assessments, and Toolkits

Brudy et al. [16] described that research on cross-device interaction can be considered as a "*constructive problem*" [111]. This is reflected in our corpus: The majority of papers focus on creating new artifacts. These papers "*push the boundaries of interaction possibilities*" [16]—a common theme for research in HCI that is often "*much better at proposing new technologies than at validating them*" [65], especially when novelty is expected as a key contribution[6]. This further fragments research on HUIs, as artifact and empirical contributions tend to drift apart [16]. While some research addressed the call for a frame of reference [16] to compare cross-device interaction techniques [166], this is still missing for research on MR-HUIs. One possibility to create such frames of reference and systematically study (and later compare) research within this space is to consider *experiments as design-informing activities* [112]. Here, different design alternatives (e.g., meaningful combinations of input and output components) can serve as independent variables for different use cases. This allows us to study their effect on general (e.g., time, error) and use case-specific dependent variables, such as utilization of devices [137]—focusing on the effect, influence, and utility of each combination, beyond a technical perspective [16].

HUIs differ from single-device user interfaces by involving multiple IO components, making assessments more complex. For example, cognitive workload (a typical metric in HCI user studies [88]) can be measured post-hoc using subjective questionnaires like NASA TLX [60], [61], but real-time, objective methods such as eye tracking are preferable [88]. As MR-HUIs often include an HWD, continuous assessment of eye movements via built-in sensors is achievable. However, switching between IO components complicates data collection, as some IO components might not support eye tracking or may have varying data quality, requiring data fusion or repeated calibration. This issue becomes more complex with multiple users frequently switching between IO components. Although subjective questionnaires simplify user studies, they reduce data accuracy, as participants might forget specific details, especially in highly dynamic MR-HUIs. Objective, real-time assessments are critical for understanding MR-HUIs, but careful study designs are necessary to manage complexity in conducting and analyzing them.

To address this complexity, research has suggested a variety of toolkits that can support this process for MR user studies [20], [67], [108], [124]. Yet, these toolkits also hold the potential to support the design, conduction, and analysis procedures of user studies involving MR-HUIs.

D. Authoring Mixed Reality Hybrid User Interfaces

Creating MR-HUIs can be challenging: Designers require evidence-based guidelines that focus on the integration of multiple devices [31], such as determining the optimal ergonomic content distribution [43], [167]. Yet, developers also need to deal with implementations on different platforms. Although web technologies (e.g., WebXR) can standardize development, their support on commercial HWDs is uncertain [17]. In addition, toolkits (e.g., for integration of multiple devices [52], IO component configuration [131], synchronization [66]) can help focus on the implementation at hand, rather than worrying about implementation details. Here, a common grammar (cf. VEGA [135], [136]) could allow content to *responsively* adapt to each device.

[6]https://sigbed.org/2022/08/22/the-toxic-culture-of-rejection-in-computer-science/ last accessed on 2025-12-01

E. Exploring Holistic Real Life Applicability

The increase in artifacts and evaluations within our corpus indicates that the nascent space represented by our corpus is slowly maturing. Research prototypes and their interaction techniques have so far been investigated in isolation, yet "*it is clear that [these] facets should not be discussed in isolation; instead, they are highly interconnected and affect each other*" [90]. Given the wide applicability of existing (see Section V-B) and future systems within our HUI subset (e.g., robotics [99], medical domain [90], [123], [143], explainable artificial intelligence [107]), we need to consider their role within the holistic context of their work environments and unveil their unique challenges and opportunities. Furthermore, consolidating common interaction techniques into a library of design patterns can help researchers and practitioners alike in the design and implementation of holistic MR-HUIs.

F. Collaboration

The majority of the papers in our corpus focus on *single-user* systems. Yet, some papers indicated a collaborative setting, either with a shared IO component (e.g., a shared output) or using individual IO components.

Regarding co-located collaboration, the choice whether there is a shared IO component or individual IO components can directly influence the type of collaboration: For example, Butscher et al. [18] used a large interactive tabletop display as a shared input device, combined with an AR HWD for each user. Limited by the touch input of the shared device, only one user is able to manipulate the content, thus enforcing a closely coupled collaboration [59], [150]. In contrast, providing users with individual IO components enables loosely coupled, parallel activities [138]. Similarly, asymmetric device setups might benefit from individual device affordances [50] but also lead to an asymmetry of roles [164].

Lastly, no papers in our corpus feature remote collaboration. In such cases, techniques known from MR remote collaboration could be applied: Virtual avatars can represent the remote person to create awareness [57], [58] while methods to align workspaces can allow for deictic referencing [49]. The use of diverse IO components might require user representations per IO component, and highly dynamic environments might benefit from transitional user representations [164].

VII. The Future of Hybrid User Interfaces

Our literature survey has shown the past and present of MR-HUIs, allowing us to infer trends for the larger domain of HUIs. However, one question still lacks clarity:

So, what is a HUI now? The term "hybrid" in HUI introduces ambiguity, as it could describe any combination of multiple interfaces and concepts. This ambiguity and divergent facilitation of the term is further demonstrated by contrasting the original definition of HUIs—referring to "*heterogeneous display and interaction*" [48] or "*different interface*" [44] technologies—with its most prevalent use today (i.e., combining 2D and MR components). This led to our decision to not sharply define HUIs and MR-HUIs because of the (1) historical developments and usages of the term, its (2) relations and overlaps to adjacent research areas, (3) the abundance of possibilities for combinations as shown in our taxonomy, and (4) potential edge cases. However, we opted to modernize Feiner and Shamash's definition of HUIs [48] (see Section II-C) while specifically focusing on the initial device combinations of 2D and MR IO components.

Through our work on this survey and our own experience, we can say that the term HUI (and with that MR-HUI) is more akin to a **fuzzy concept**—"*a collection of objects [that do] not have sharp, clear-cut boundaries*" [21]. Thereby, HUIs can be characterized with certain attributes as described in Section II-D. In the end, actual manifestations may vary—depending on the discussed ever-shifting window of opportunities—where HUI boundaries remain adaptable to emerging interaction paradigms, technological affordances, and contextual demands. However, if the term is adaptable in such a way, we must ask:

Will there be HUIs in the future? On the bright side, HUIs combine complementary device technologies, taking advantage of the strengths of each technology, creating user interfaces where "*the real power [...] comes not from any one of these devices; it emerges from the interaction of all of them*" [157]. This combination can create flexible and modular systems in which the user can freely decide when to employ which type of feature (i.e., IO component).

However, from a rather critical perspective, HUIs could be considered as a compensation mechanism for the deficiencies of individual IO components, such as the limited precision of gesture recognition in AR environments. By including additional technologies to address the shortcomings of any one input method, these systems can become too complex to design, evaluate, and eventually use. With advances in technology, the need for HUIs composed of multiple IO components may diminish: An ultimate interface might not require the combination of multiple IO components to compensate for individual weaknesses. Instead, at some point in the future, there will be self-contained "devices" that streamline interaction into a single cohesive system. This leads to the question:

Is there an expiration date for HUIs? We believe so, but cannot say when. Over 30 years of research on HUIs and related research streams have shown a maturing of concepts and usage of technology. Although some of the pioneering works are often technology-driven, proving the feasibility of hardware-heavy combinations, newer works are more mindful of the usage of technology. At the same time, we observed an increase in various evaluation strategies over time. Both can be attributed to advances in technology (e.g., advanced built-in tracking capabilities)—minimizing the need for additional technical augmentation while focusing more on the user of such systems. This shifts the focus from purely technical work towards studying the individual benefits of various design alternatives (e.g., different variants of HUIs) and emphasizes the value and utility of individual IO components and the user experience of HUIs. This maturing process led to current off-the-shelf devices (e.g., Apple Vision Pro[7]) and applications (e.g., Immersed[8]), which already bring HUIs to the consumer market. With the maturation of concepts, an increase in empirical contributions, the advent of

[7]https://apple.com/apple-vision-pro/, last accessed on 2025-12-01
[8]https://immersed.com, last accessed on 2025-12-01

consumer-oriented HUIs, and the development of research areas such as artificial intelligence or even brain-computer interfaces, we can take a step back and look at the bigger picture with a last question:

What does the future of HUIs look like? With our attributes, we identified a classification of past and current MR-HUIs. The interplay of IO components is fundamental for HUIs: A typical HUI consists of multiple IO components in heterogeneous roles, complementing each other, and forming a single application. Past and present HUIs often consider “IO component” as a synonym for “device”—creating a cross-device interaction. However, by reconsidering what constitutes an IO component, we can draw inspiration from concepts such as *complementary interfaces* [163] and related ideas [40]: These concepts are device-agnostic, opening up the research space for combinations of IO components beyond devices and avoiding being trapped in technological restrictions. Here, new meaningful combinations of IO components that include different input and output modalities, combinations of implicit and explicit interaction, and various interaction techniques provide an avenue of research opportunities. Thus, we can expect a change in how HUIs will be designed, built, and evaluated until they eventually disappear when approaching the “ultimate display” [148].

VIII. Conclusion

We investigated three decades of research in the field of hybrid user interfaces by revisiting their definition, reframing HUIs as a fuzzy concept, and discussing future directions. Despite inconsistent prior usage of the terminology, we identify shared aspects, such as the combination of heterogeneous devices and the merging of visual and interaction spaces. This combination is especially appealing for mixed reality environments, offering unique opportunities and addressing inherent shortcomings by using a complementary 2D interaction device, and has been extensively explored in prior work with inconsistent terminology. Our literature survey, therefore, takes a closer look at hybrid user interfaces that combine mixed reality environments with 2D devices and presents a taxonomy of key characteristics. We see our work as a starting point, enabling the larger community of researchers and practitioners to share their insights and inspire novel systems and interaction techniques.

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