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Mixed reality prototyping: a framework to characterise simultaneous physical/virtual prototyping

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Abstract

Immersive reality (XR) technologies, particularly Mixed Reality (MR), offer promising opportunities for enhancing design prototyping. While recent studies often focus on Virtual Reality this work explores the application of MR, where focus lies on interlinking both the physical and digital to maximise benefit. Following a review of XR in design, a descriptive framework is presented to characterise MR prototyping. Two case studies are then presented to highlight the value of bridging the physical and digital worlds, before directions for further research in MR-based prototyping are outlined.

Keywords: prototyping, virtual reality (VR), virtual prototyping, mixed reality (MR)

1. Introduction

Prototyping is a vital part of the design process (Ulrich and Eppinger, 2016), captured in many formal models and with considerable interest from the research community. Through prototyping activities, designers evolve their understanding and the design itself, with resulting prototypes used for many purposes (Menold et al., 2017), such as learning, communication, exploration, and refinement (Camburn et al., 2015; Otto and Wood, 2001). While definitions vary, many agree that prototypes are *'an approximation of the product along one or more dimensions of interest'* (Ulrich and Eppinger, 2016) that can comprise a vast array of potential media (Camburn et al., 2017) across levels of sophistication (Pei et al., 2011). As each media holds its own affordances and costs (Snider et al., 2023) the array of options available leads to uncertainty on how best to prototype (Goudswaard et al., 2021), and which prototyping method to select (Lauff et al., 2018).

Of particular interest are the affordances provided by physical (e.g. card, AM, mechanical) and virtual (e.g. CAD, simulations) prototypes (Snider et al., 2023), with both domains playing a critical role and offering distinct affordances (Kent et al., 2021a). As the weakness of one domain often balance against strength in the other (Kent et al., 2021a), the manner in which physical and digital prototypes may be concurrently leveraged to maximise value stands as a promising area for research (Snider et al., 2022).

There has also been rapid development of Extended Reality (XR) technologies and interest from the design community exploring implementation, applications, and benefits. The manner in which XR has been applied to design research has varied, but often tended towards Virtual Reality (VR), in which a person is immersed in a fully digital world through the use of a headset, with spatial interaction actuated physically by their own natural movement. While understanding of the value of XR in design is steadily growing, less attention has been given to the way in which it enables the physical and virtual worlds to be interlinked and work together. Given the critical role both physical and virtual prototyping play in design and the potential for MR technologies to support their integration (Snider et al., 2022), the application of MR to prototyping is a promising opportunity to support prototyping activities.

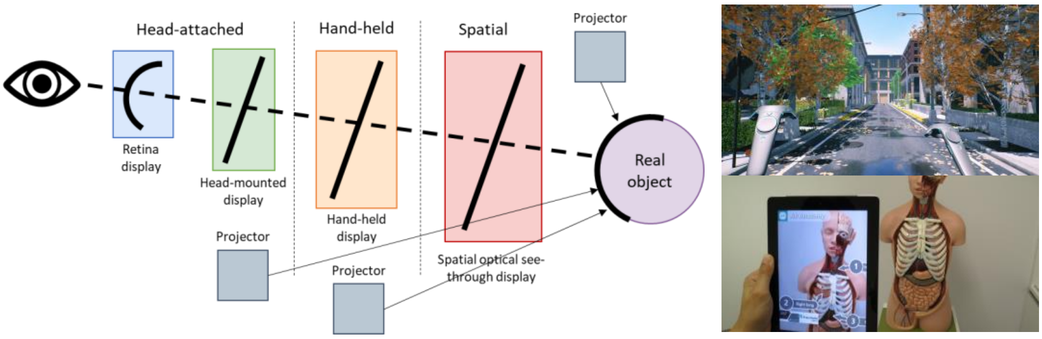

Figure 1. (Left) Mixed reality types, adapted from (Bimber and Raskar, 2006); (Right) Virtual and augmented reality experiences[1]

With research in XR in design still in it infancy, this paper explores it's characterisation and application to design prototyping in order to formalise and provide a framework to support future reporting and discourse on the subject.. The framework is then used to review state-of-the-art of XR design research and to characterise three XR prototyping implementations, demonstrating descriptive capability and establishing research gaps, opportunities for future research, and challenges.

2. Background: the use of mixed reality in design prototyping

To establish the value and foundation for the framing, this section will discuss the affordances of prototyping media, and XR technologies as currently applied in design and prototyping.

2.1. The importance of physical and virtual prototyping media

It is well understood that the media used to create a prototype will influence the activity (Camburn et al., 2017, 2015; Snider et al., 2023), it's efficiency, cost (Christie et al., 2012), and eventual success. Different media and approaches align with different prototyping purposes, hold varying levels of precision and specificity (Pei et al., 2011), and hence align to different process stages and design activities. For example, looking at the prototype types of (Houde and Hill, 1997) *(look/feel, implementation, role)*, it stands that the media one may require to create a high quality lookalike prototype that does not need to replicate function (i.e. a static 3D printed model) may be different to that which iterates functional performance (i.e. a motion-simulating virtual model). Identified affordances of different media are broad, including such properties as fidelity, flexibility, interactivity, accessibility, and resource cost (Snider et al., 2023).

The relative strengths and weaknesses of physical and digital prototyping media has also received attention. Both play crucial roles in prototyping, but hold contrasting and counterpoint benefits (Kent et al., 2021a). While the tangibility and physical presence of physical prototypes allows direct and realistic interaction for a wide range of stakeholders and hence gives excellent understanding of feel and implementation, such prototypes are often expensive one-offs, with little option for re-use. Conversely, a digital model and simulation of the same prototype has the ability to be rapidly reconfigured and re-used, but lacks the tangibility that many stakeholders require to form judgements.

Further, there is a cost in iteration between physical and virtual prototypes, where each must be updated to reflect changes in the other. With many prototypes needed to achieve goals this risks inefficiency; managing the transition between models increases quantity and time taken by design cycles.

2.2. Extended reality technologies in design

Given this reliance on a myriad of physical and virtual models throughout design prototyping, it is not surprising that recent work has turned to the capabilities provided by Extended Reality (XR)

[1] Open-source image from: https://pixabay.com/photos/augmented-reality-medical-3d-1957411/

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technologies. XR is an umbrella term for a wide range of technologies and implementations, typically described through their location on the Virtual Reality Continuum (Figure 2) (Milgram et al., 1994) with location often determined through display type (Bimber and Raskar, 2006). This continuum primarily distinguishes through the relative role of virtual and real elements, ranging from digital objects overlaid onto real environments (Augmented Reality - AR) to the less-common physical objects placed in simulated virtual environments (Augmented Virtuality - AV). In general, implementations between fully real and fully virtual are termed Mixed Reality (MR).

While the merging of physical and digital into a single interface is well-studied, the recent maturation of MR-capable technologies has enabled their application in domains ranging from education (Hallmann et al., 2023), to architecture (Kim and Hyun, 2022), to design (Verlinden and Horváth, 2009). Several works have highlighted the importance of the viewing interface for design performance (Berni et al., 2023; Horvat et al., 2022; Nandy et al., 2023) noting differences when using XR compared to traditional modes. Benefits of XR implementation for design have been shown to be broad, including enhanced spatial reasoning (Horvat et al., 2022), divergence (Sopher et al., 2022), confidence and satisfaction with outcomes (Kim and Hyun, 2022), and collaboration (Bisson et al., 2023).

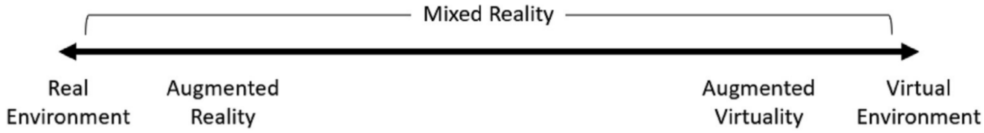

Figure 2. The Virtual reality continuum, adapted from (Milgram et al., 1994)

2.3. Mixed reality in prototyping

While all locations on the continuum between real and virtual are often termed MR, researchers have highlighted the importance in MR of considering the degree and form of inter-linking between physical and virtual domains (Rokhsaritalemi et al., 2020) when creating interactions. While in AR and AV this interaction may be minimal (i.e. static digital overlay placed in the physical world, with no means of interaction), increasing inter-linking has potential to create rich experiences with high complementarity between domains, increasing interactivity and supporting learning (Rokhsaritalemi et al., 2020).

This focus on physical-digital interlinking is of key interest when considering XR prototyping. MR proposes an opportunity to maximise the value of XR in design by considering how each domain may be best used and combined to create a single, streamlined activity. In other words, allowing the prototype to be the core of the implementation with physical and virtual elements chosen around it to maximise benefit for that prototype and activity. See Fig.3 for an example.

Figure 3. Example affordances of MR prototyping implementation

2.4. Summary

With a myriad of prototyping media, each with individual inherent affordances that influence their utility across activities, products, and users, it is critical that research into prototyping technologies considers how media may be best leveraged to support activity. By creating a bridge across a fundamental distinction between media - that of physical and digital - XR technologies hold huge potential to enhance prototyping processes and maximise value. However, while several recent works have demonstrated the value of XR in design, specific consideration of the interplay between physical and digital domains may

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be leveraged is lacking. To maximise the key affordances of each domain (i.e. tangibility and accessibility of the physical, flexibility and analysis of the virtual (Kent et al., 2021a)), there is a need for characterisation of MR as applied to design prototyping, determining the constituent elements of an MR implementation and how they may best be utilised. Such a framing will allow better understanding of MR prototyping, comparison and situating of different implementations, and hence lead towards development of improved prototyping technologies.

3. A framework for MR in design prototyping

Prototyping as an activity is centred on learning and development of an output by a designer (Camburn et al., 2015), through interaction with and analysis of a prototype. Any framing must then recognise the role of the product, the user, and the interaction between the two. Equally, the environment in which the prototyping activity occurs influences the activity itself and its outcomes (Kaplan et al., 2021), as repeatedly underlined by research considering the role of the environment on ideation (Nanjappan et al., 2023) and design activity (Hu et al., 2023; Trump and Shealy, 2023). Similar framings of design as the interaction between person, product, and environment are present across literature (i.e. see (Snider et al., 2022)), including in technical implementations of XR (Kent et al., 2021b).

The flexibility of the virtual domain also makes it necessary to explicitly consider product/environment interactions. As physical and virtual may be decoupled, potential exists to vary how they interact, from entirely reliant to not at all (Snider et al., 2022). For example, a virtual model may be spatially located but otherwise float statically, or may be subject to simulated physics and interact with the real environment geometry. Just as the MR system creates options in the interaction between the user and system elements, it also creates options in how system elements may interact between each other.

3.1. Real, virtual, actual, and augmented

MR provides the opportunity to represent elements physically, virtually, or in some combination (Milgram et al., 1994; Rokhsaritalemi et al., 2020). With varying affordances of each media, it then stands that the domain in which the product or environment are represented will influence the activity itself, and that careful selection and combination of physical and virtual across elements may allow leveraging of affordances to create additional value.

In this sense representing in MR creates substantial flexibility. By leveraging the virtual, tools may augment and manipulate both the real and virtual world beyond that which is possible in the real world (Farshid et al., 2018). Here, framework elements may be aligned to the real world (i.e. in aesthetic, physics, environment), then making user interactions similarly true to a 'real' physical product, or may be virtually augmented with alternatives, behaviours, and other properties beyond that which is otherwise possible. This creates option for (i.e.) new experiences, different viewpoints, and product options rapidly and without the constraints of fabrication.

Augmenting hence allows either streamlining of prototyping by using the virtual to recreate physical elements (reducing fabrication needs), or exploration through (i.e.) virtual augmentations that remain grounded in physical products or environments. This raises a decision point for MR prototyping systems in whether they focus on realism or augment system elements, and the benefits that each provides.

3.2. Mixed reality prototyping

MR prototyping must then consider that the product and the environment may be represented either *physically* or *virtually*, and that the virtual may represent either *realistically* or may *augment* beyond.

Aggregating these creates the framing as shown in Fig.4, encompassing the elements within the prototyping activity (product and environment), their interaction between each other (behaviour) and with the user. The following paragraphs detail each element and value propositions that they create.

1: Product: The representation of the prototype within the system. The form of any prototype may vary considerably depending on its intended purpose (Houde and Hill, 1997; Ulrich and Eppinger, 2016), with accompanying impact on activity success as well as efficiency, skill level, and cost (Christie et al., 2012). Within an MR product, physical and digital elements may be simulated as if real, or may be augmented through for example new aesthetics, possible geometries, and simulated function. While the

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mixing of affordances of each media in a single object has substantial potential (Kent et al., 2021a; Verlinden and Horváth, 2009), large challenges remain in effective synchronisation of physical and virtual product counterparts, especially in real-time and for evolving products (Kent et al., 2021b).

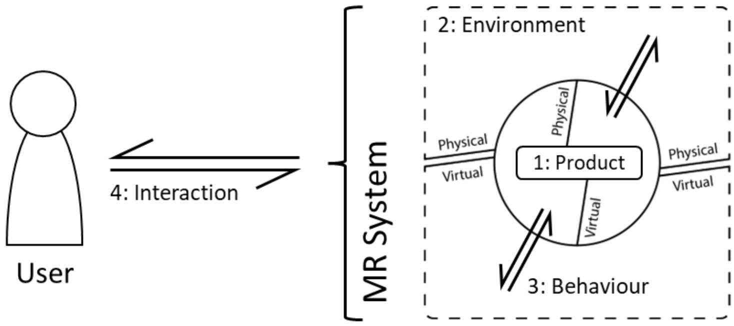

Figure 4. The MR prototyping framework

2: Environment: The environment in which a prototyping activity occurs has been shown to negatively influence outcomes if it is sufficiently different to that in which the final product will be used (Kaplan et al., 2021). While VR creates immersion through a virtual environment, MR gives the option for products to be placed in the real world, for virtual worlds to be made tangible through placing real geometries in the space around the user, and for the real world to be augmented through virtual additions.
3: Behaviour: The behaviour of the product within the environment. For many prototyping activities, how the product and its environment interact forms a core part of their purpose. In MR the inter-reliance between product and environment may be relaxed or otherwise controlled, creating option for products to ignore the environment, to respond to it realistically, or to augment through simulation of new or otherwise impossible behaviours (i.e. altering environmental conditions and their impact on a product).
4: Interaction: The interaction between the user and both the product and the environment. As an activity focused on learning, the user/prototype interaction is core to activity. In VR interaction typically occurs through spatial movement with physical controllers, although more immersive interfaces are emerging that increase physicality and realism (i.e. gesture-driven, haptics). In addition to these control schema, in MR a user may interact with a product or environment directly through methods that mimic physical interaction, or augment with new interactions beyond what is possible in the real world.
Summary: Across each elements, the flexibility of working across the physical and virtual creates new opportunities for prototyping activity that may be used to create more realistic experiences, and augment beyond what is usually possible. Two primary benefits here lie in enhancing learning across stakeholders and in process streamlining, both achieved by leveraging affordances of working in each domain. For example, augmenting tangible physical prototypes with simulation results leverages the flexibility of the virtual to increase learning with while minimising physical testing, or augmenting low fidelity physical prototypes with high fidelity virtual aesthetic creates a better representation of a final product that may also be altered in real-time, without fabrication time and costs. However, while studies are beginning to explore such opportunities, the way in which each domain may best be leveraged is as-yet unknown, as is the degree to which it counterbalances the potential high cost of implementation. To illustrate the framework in action this paper continues in two ways; [1] a classification of recent exemplars of MR systems in design literature clarifying state of the art, and [2] evaluation of three case study implementations, illustrating the framework and extracting challenges, value, and research need.

4. Design literature in MR - state of the art

To demonstrate the framework and examine current discourse, papers from the past three years of the Design Society (DS) repository that contained the terms 'Mixed Reality', 'Extended Reality', 'Augmented Reality', or 'Virtual Reality' were downloaded. Recent DS papers were selected to maintain strict focus on state-of-the-art design-relevant research. This resulted in 130 papers. Those not clearly demonstrating an MR system were excluded, with 22 papers remaining. Their MR systems were then coded via the framework. Coding considered whether each element was present, represented simply or by default XR behaviour (i.e. basic geometries, default controller-driven interactions), represented in a

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way realistic to the real world or the product, or augmented beyond the real world by leveraging the virtual domain (i.e. gave 'impossible' viewpoints, exploration of new geometries).

Table 1. Coding of extant literature cases[2] by framework elements; Key: (-) not present or clear; (S) simplified representation; (R) realistic representation; (*) augmented representation

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
Product Virtual	-	-	-	-	-	S	S	-	*	*	-	R	R	R	R	R	S	R	R	*	-	R
Product Physical	-	-	-	-	-	-	-	-	-	-	-	S	-	R	-	-	S	-	-	-	-	S
Env. Virtual	*	*	R	*	*	S	S	R	S	-	R	-	-	R	-	R	*	S	*	S	R	-
Env. Physical	-	-	-	-	-	-	-	-	-	R	-	S	R	-	S	-	-	-	-	-	-	R
Behaviour	-	-	-	-	-	S	S	-	*	R	-	-	-	R	-	-	S	S	-	-	-	-
Interaction	S	S	*	*	S	S	*	S	*	-	S	S	*	R	*	*	*	*	R	*	S	S

Prevalence of elements within MR prototyping systems: While most cases did not purport to be MR, as all exist on the VR continuum it is interesting to review how they have represented each framework element. Few papers (L, N, Q, V) ground their representations on a physical product, instead choosing to locate a virtual model in a physical environment, or in a virtual environment, or working with a virtual environment alone. The elements of physicality present are typically through interfaces, where standard VR control schemes require spatial locomotion to function. Several works carefully considered the form and role of virtual environment, but few extended this to the physical. Where it was considered it only used the environment as surroundings, rather than as an interactive element to interact with a product.
Product / Environment Interlinking: A minority of systems considered the interlinking between products and environments, often relying on default VR world behaviour (i.e. models floating in space), or virtual models with high dependence on physical interfaces. Where physical and digital were realistically interlinked (J, N), they comprised reactive virtual models and/or physical haptic feedback.
Augmentations and realistic representations: Many systems utilised the flexibility of the virtual domain to augment the experience. This typically occurred in Interaction, where switchable viewpoints, analytics, and additional information were pushed to the user. Others augmented the environment, for example creating colour-deficient worlds to test colour blindness (B), or environment sets to test the impact of their immersion on design activities. Very few augmented the product, instead creating realistic representations. Those that did so created see-through views (J) and highly manipulable geometry (I) to allow exploration and encourage understanding.
Summary: The framework has elucidated several findings for the state of MR research in the field. It is perhaps notable that few implementations of the set were design focused - while they considered geometry, part options, design review, etc., they were often not intended to allow design exploration or manipulation, instead being immersive viewers for models as boundary objects. Given the flexibility generated by the virtual domain, exploring in more detail how it may be used for technical design variation and exploration is an interesting opportunity. Further, few systems explicitly considered how the physical domain may be leveraged, with even fewer considering how the virtual and physical domain may be interlinked to create emergent value. Again, this forms an interesting avenue for research.

5. Illustrative case studies

With few direct exemplars in literature, this section presents and draws observations from three MR prototyping cases developed by the authors[3], see Fig.5 and Table 2. These demonstrate the descriptive capability of the framework, identify value propositions, and areas for future research.

[2] References for works: A (Scurati et al., 2023), B (Hu et al., 2023), C (Latif et al., 2023), D (Trump and Shealy, 2023), E (Nanjappan et al., 2023), F (Steinhauser et al., 2023), G (Horvat et al., 2022), H (Berni et al., 2023), I (Nandy et al., 2023), J (Hireche et al., 2023), K (Bisson et al., 2023), L (Hallmann et al., 2023), M (Harlan et al., 2023), N (Brunzini et al., 2021), O (Yengui and Stechert, 2021), P (Seybold and Mantwill, 2021), Q (Porro et al., 2022), R (Goethem et al., 2021), S (Mariani et al., 2021), T (Romero et al., 2021), U (Kujur et al., 2022), V (Melo et al., 2022)

[3] See https://tinyurl.com/DMFdrill, https://tinyurl.com/DMFcontroller, https://dmf-lab.co.uk/our-lab/

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Value propositions of the Cases: By leveraging MR, the cases demonstrate how the virtual may accelerate prototyping through rapid exploration, without the need for physical fabrication (i.e. through variable aesthetics (Case 1), simulated function (Case 2)). Particularly in Case 1 and 3 this allows the physical elements to be reduced to very low fidelity further lowering cost and complexity, with virtual overlay essentially hiding the imprecision of the physical counterparts. In this way VR may be used to manipulate the senses, increasing variety and flexibility of systems. All cases also successfully maintain high tangibility and accessibility, creating familiar and believable physical interactions in line with a users expectation, despite the low quality and lack of functionality of the actual physical object.

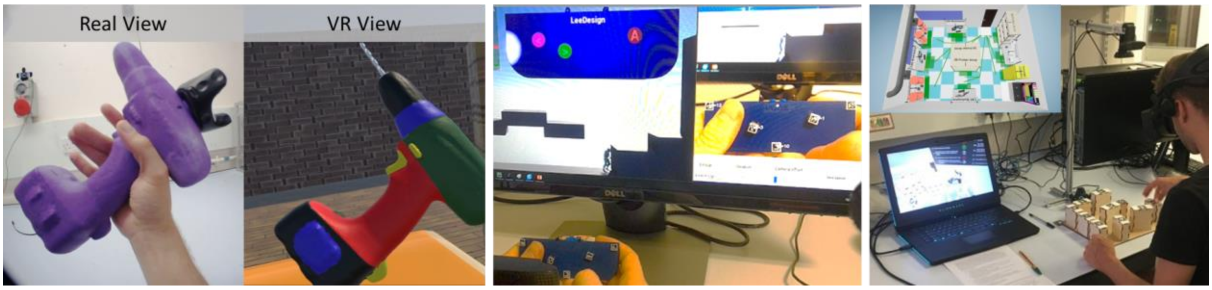

Figure 5. MR case studies; (left) Case 1: Synchronised physical / virtual drill; (mid) Case 2: Reconfigurable controller; (right) Case 3: OurLab

Table 2. Framing for each case

Case 1: Synchronised physical / virtual drill for product reconfiguration A physical drill is tracked in 3D space and mapped 1:1 in real time to a virtual counterpart. Through a VR interface, the user may interact with the physical prototype and see the virtual move. The physical model is modular, with options across a range of masses and dimensions. The virtual may be altered for aesthetic.			
Product	***Environment***	***User Interaction***	***Behaviour***
P and V synchronised. Simplified P augmented with V geometry and aesthetic.	P and realistic V. V augmented with P table mapped to V space.	Realistic P user interaction with V visual. P augmented via modular parts, and with simple V controls for aesthetics.	V dependent on P, creating realistic behaviour.
Case 2: Reconfigurable controller for interface design A physical touch-sensitive controller has positionally-tracked buttons that may be freely affixed by the user. Button placement and presses are captured, and used to simulate full function in a simple game. A virtual model of the controller is shown on-screen.			
Product	***Environment***	***User Interaction***	***Behaviour***
Primarily P, augmented with reconfigurable buttons. V augments with aesthetics and function.	P only, in the user's current environment.	Realistic P user interaction. Viewed in P or simplified V. P augmented via reconfiguration.	V augments P, simulating realistic as-final product behaviour.
Case 3: OurLab - Room-scale layout planner with in-built analytics A physical desk-scale representation of a room is manipulated by the user, with scaled blocks representing equipment. These are synchronised to realistic virtual versions that may be viewed in two forms of VR; full-scale (i.e. user in the room) and small-scale (i.e. room aesthetic overlaid on physical models).			
Product	***Environment***	***User Interaction***	***Behaviour***
P and V synchronised. Simplified P augmented with V showing realistic geometry and aesthetic.	V only, realistic. Augmented with switchable scales and viewpoints.	P interface with augmented game-like movement. Viewed in V augmented with view switching.	V depends on P. Augments through embedded performance analyses.

Virtual augmenting of physical elements: Much value is achieved through the augmentations that the virtual enables, typically creating benefit in process streamlining. Case 1 reduces the need for high-fidelity physical fabrication via augmenting with virtual aesthetics and environment and physical modularisation. Case 2 augments with simulated function, removing the need for physical electronics. Case 3 augments with varying scales, viewpoints, aesthetics, and embedded real-time analysis. In all

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cases, the elements of flexibility that these augmentations create would not be available in solely physical prototypes, nor would their speed and accessibility be possible solely in the virtual. With that said, augmentations all created higher degrees of functionality or variety while also increasing realism, rather than fully unlocking the flexibility of the virtual by branching beyond the possible. With examples that do move beyond the real showing promise in literature, such extensions of augmentation are an interesting opportunity for future research.

Technical implementation challenges: In each case, the MR system required substantial bespoke programming, physical sensing, and calibration. While all using low-cost hardware, creating real-time synchronisation between physical and digital required a range of custom software and careful calibration. All augmentations were fully bespoke to the specific case. Creating realism when anchored in virtual required careful testing and refinement. As such, to realise value in industry, the Cases illustrates the need for targeted tools and methods to streamline MR for prototyping, developed to maximise value in a broad range of cases.

6. Discussion

MR in design has increasingly been a focus for many researchers, with several systems presented in recent years. MR itself has excellent potential to streamline the design process and increase understanding, through leveraging the flexibility of the virtual, with the tangibility of the physical, and careful interlinking between the product, environment, and user. While several researchers are investigating value propositions of MR, fewer are currently fully leveraging the capability that it offers, integrating the physical to a high degree, and/or using it scenarios beyond immersive viewing of static geometries and environments.

Framing Utility: The framing employed draws on well-documented definitions of MR, and promotes the value and flexibility introduced through virtual augmentation. It has proven applicable to each studied case and has allowed fair comparison of each, as well as identifying gaps and opportunities for future work. It is not however complete; other works have also considered the form of interlinking between domains through their intersection and dependence (Snider et al., 2022), and methodologies for creation of MR systems (Lingan et al., 2021). Augmentation may occur in many different ways, and the form of augmentation (i.e. simple visuals vs. complex physics) may greatly affect both learning and cost. As a result, there is value in further extending understanding to characterise such elements in more detail, and thus to clarify the relative value that each has potential to provide.

Questions for future work: As discussed, the framework has provided several avenues for future work. MR has proven potential in a wide range of scenarios, but there is insufficient study to extract the specific value propositions of the different implementation options that exist. In all reviewed cases and studies, the use of MR created research opportunities, learning, and understanding beyond that which would be possible in a single domain alone. Given the variant affordances of media, there should be study on exactly what should be physical and virtual in order to maximise benefit for a given activity. Further, the way in which the product/environment/user and physical/virtual may be interlinked is highly variant, as is the opportunity for augmentation through virtual. Again, future study should consider the specific value propositions of different forms of each. Finally, the technical overhead of building each implementation should not be ignored - near-all are substantial bespoke design efforts. There should then also be focused work on common toolchains and ways of working that are broadly applicable, such that tools with wide utility may be developed that can be employed in many scenarios.

7. Conclusion

This paper has presented and demonstrated a framing for MR prototyping in the context of design, extracting detailed state-of-the-art, identifying gaps in research, and opportunities for future work. Considering the different affordances of physical and virtual, the role of the product, environment, and user, and the flexibility of the virtual domain, it has presented the potential value that MR may provide and its specific relevance to technical prototyping. While the pace of recent research has been rapid, there are many opportunities yet to be realised, which may be investigated for value, tensioned against cost, and leveraged to streamline design and prototyping activities.

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