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Improving Mixed-Reality Prototyping through a Classification and Characterisation of Fidelity

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Abstract

Prototyping is a vital activity in product development. For reasons of time, cost and level of definition, low fidelity representations of products are used to advance understanding and progress design. With the advent of Mixed Reality prototyping, the ways in which abstractions of different fidelities can be created have multiplied, but there is no guidance on how best to specify this abstraction. In this paper, a taxonomy of the dimensions of product fidelity is proposed so that both designers and researchers can better understand how fidelity can be managed to maximise prototype value.

Keywords: prototyping, virtual prototyping, design tools, ontology, augmented reality (AR)

1. Introduction

Prototyping is a valued and critical activity in the design process (Camburn et al., 2017). Traditionally carried out in the physical domain, prototyping has since expanded to also include the virtual domain, thanks to advances in computing technology. Both domains have distinct advantages and disadvantages (Kent et al., 2021). Virtual prototypes' main advantage is the speed with which they can be created, modified, and duplicated, reducing the time and effort to create a model. Physical prototypes often require more time to develop due to fabrication, however, a physical prototype is far more interactive as it can be handled and perceived with our sense of touch. These complementary advantages mean that prototyping often features a range of activities across both domains (Kent et al., 2021).

The past decade has seen a rise of Mixed Reality (MR) prototypes, where the tangibility and validity of physical models is combined with the flexibility and replicability of virtual models (Kent et al., 2021). Fully physical or virtual prototypes can be easily defined as such, but MR prototypes exist on a spectrum between the two domains (Milgram et al., 1995). At one end of this spectrum there is 'Augmented Reality' where virtual elements are added to a physical model, such as the SPARK platform (O'Hare et al., 2018). At the other end of the spectrum is 'Augmented Virtuality', where physical elements are added to a virtual model; for example, adding physical props to a VR scene. This sliding scale of 'domain-sionality' provides the opportunity to mix physicality and virtuality at different levels of fidelity, and prompts the question:

> *What is an appropriate combination of fidelity and how can this affect the feedback/insights generated during prototype evaluation?*

To answer this question, it is first necessary to characterise and classify MR fidelity. The contribution of this paper is the proposal of a taxonomy of fidelity that will provide the foundation for longer term work investigating and characterising the required fidelity level and mix of domains for MR prototypes. The novelty lies in the holistic view of this taxonomy, looking in depth at multiple sensory pathways, as well as the functional realism and user behaviour. Each of these factors should be considered when creating an MR prototype and there is currently little or no literature that encapsulates all these factors.

2. Related Work

This section covers an overview of MR prototyping and examples of previous work. From this, evidence of the importance of fidelity control and the challenge of describing fidelity for MR is highlighted.

2.1. Mixed Reality Prototyping

Mixed Reality (MR) prototypes have grown in popularity due to advances in MR technology that have democratised the development of MR prototyping tools and facilitated the creation of higher fidelity prototypes in less time (Kent et al., 2021). As this field is relatively new, there is little consensus on the best method(s) and/or guidance for implementation within engineering/design contexts. Much like physical prototyping, there is a range of different methods, with varying fidelity levels, that are suited to different situations (Camburn et al., 2017). It will be up to the designer to select a suitable type or implementation of MR prototype for their specific design problem. Several MR technologies have already been used for MR prototyping and can be divided into two categories: Virtuality and Physicality. Virtuality generates the virtual component of the prototype and is mostly related to the visual aspect. Physicality is responsible for how the prototype interacts with the user, and the physical world around them. Typical tools used are shown in Table 1.

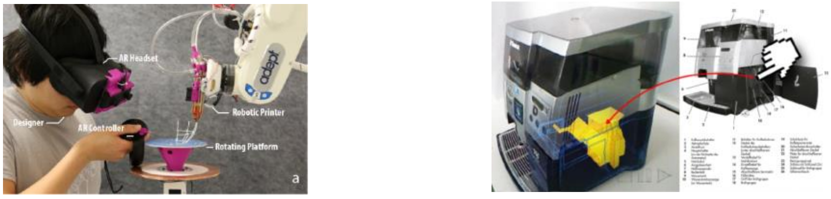
Table 1. Examples of tools used for Mixed Reality Prototypes

Virtuality/Physicality	MR Prototyping technology	Example(s)
Virtuality	Mixed Reality Headset	Microsoft HoloLens, MagicLeap, etc.
Virtuality	Virtual Reality Headset	Valve Index, Oculus Rift, etc.
Virtuality	Screen-Based Augmented Reality	Pokemon Go, Vuforia, etc.
Physicality	Haptic Gloves	HaptX, Dexmo, etc.
Physicality	Robotic Arm (Force Feedback)	Mantis Force Feedback, Kuka, etc.
Physicality	Motion Tracking and Capture	Kinect, Leapmotion, Fiducials, etc.
Physicality	Physical Substitute Model	Rapid prototype, Junk prototype

Several studies have used these technologies to evaluate the performance of MR for prototyping (Figure 1). While each of these examples contain physical and virtual components, the difference in fidelity of the components is variable and often not clearly reasoned. For example, there is no reason given to why the virtual overlay in Figure 1d is rendered only as yellow and not with realistic colour, or why the fiducial markers in 1a must be the size that they are, relative to the actual button sizes.

(a) A low-cost, interactive AR DJ table planning tool, with fiducial markers used to imitate the operation of buttons, sliders and rotating parts. (Kelly et al., 2018)

(b) A 3D sketching tool, where 2D shapes can be sketched on a panel, and virtual 3D shapes can be extruded or revolved. (Reipschläger and Dachselt, 2019)



(c) A human-robot collaborative 3D printer. Partially printed models are used as a reference for new elements. (Peng et al., 2018)

(d) A virtual overlay of internal components is superimposed over the physical artifact. (Mohr et al., 2015)

Figure 1. MR Prototypes with varying fidelity in both the physical and virtual domains

Although brief, this review of applied MR prototyping reveals that MR provides a vast scope and multi-dimensional space in which to configure prototype fidelity. It has also revealed that much of the current research focuses on exposing the art of the possible. To take MR prototyping forwards, towards real-world application, research is required to understand what fidelity is required and how to realise it.

2.2. Previous Work Classifying Fidelity in Mixed Reality Prototypes

Previous works have made an effort to characterise aspects of MR fidelity. In a taxonomy of MR visual displays (Milgram and Kishino, 1994), several characteristics are proposed to define the visual fidelity of an MR system. These include stereoscopic vision, ray-tracing and shading/texture/transparency. However, the capability of virtual displays has significantly improved since 1994 and these characteristics may no longer be appropriate as differentiating factors.

Other work investigating prototype fidelity in software development highlights that a simple scale of low to high fidelity is insufficient to fully describe the fidelity of a prototype. Instead, it breaks down fidelity into: *Level of Visual Refinement*, *Breadth and Depth of Functionality*, *Richness of Interactivity* and *Richness of Data Model* (McCurdy et al., 2006). However, this breakdown may not be appropriate or have a one-to-one mapping to physical product development.

Fink and Shriver break down MR fidelity into three components (Fink and Shriver, 1978):

1. **Physical** - The extent that a prototype duplicates the *appearance* and *feel* of what it is representing.
2. **Functional** - The extent that a prototype duplicates stimuli present in the *operational environment* and the ability to respond to those stimuli.
3. **Psychological** - The extent to which the user perceives the prototype as being a duplicate of what it is representing and *behaves* and *interacts* with it as they would the real product.

Some work has looked at and confirmed the importance of multi-sensory MR prototypes (Bordegoni and Ferrise, 2013). However, there is little-to-no justification of why the selected sensory modes were chosen, what components of these senses were most important, or the fidelity level used for each sensory mode. This work exposes a gap in the field's understanding of the different sensory modes that can be emulated, what they consist of and what fidelity should be used, in order to maximise the value of an MR prototype for the lowest costs.

3. Fidelity in Mixed-Reality Prototyping

The fidelity of an object can be described as:

> *‘The degree of exactness with which something is copied or reproduced’ (Oxford University Press, 2021).*

As a designer has control over the ‘degree of exactness’ of a prototype's production, and MR prototyping offers a vast range of potential fidelity, it is vital to understand what an appropriate degree of exactness is. As such, a deeper understanding of fidelity is required to make an informed decision.

Taking the creation of a new cordless drill, for example, will likely involve several different implementations of MR prototype with different levels of physical and virtual embodiment to create the necessary levels of haptic and visual fidelity. Three potential MR prototypes are shown in Figure 2. Figure 2a shows an AR-based prototype that allows the drill to be displayed in a real environment through a smartphone. Figure. 2b shows a projection of a colour-map on a blank 3D model of the drill, using the SPARK system (O’Hare et al., 2018). Figure 2c shows a prototype made using a substitute model, with a virtual model in VR tracked to the position of the physical part.

Each MR prototype would be difficult to place on a simple scale of low to high fidelity due to the varying levels of fidelity for different sensory modes. However, each of these prototypes is suited to a different task due to these differing fidelity profiles. For example, if one was trying to quickly test the effect of different mass properties on user perception, the third option could be considered most suitable. However, if a design team was assessing different colour schemes, the first two options would be a better choice. Within these two options however, the first option costs a fraction of the second, but also requires a smartphone to act as a ‘portal’ to see the prototype which has been shown to be less preferable

a) Augmented Reality Prototype using Vuforia. A virtual drill is added on top of a marker

b) Spatial Augmented Reality Prototype using SPARK. Colour is projected onto a blank 3D version of the product.

c) Prototype using a virtual reality overlay on top of a blank 3D version of the product.

Figure 2. Three different MR prototypes of the same product

to the projection system due to a lack of immersion (O'Hare et al., 2018). As such, an understanding of the different components of fidelity will aid designers in creating prototypes that can cater to their goal.
To further understand the fidelity of MR prototypes, the authors posed four questions: 1) How do we classify fidelity? 2) How does fidelity vary? 3) How do we measure fidelity? 4) What level of fidelity is needed? The first of these questions will be answered in Section 3.1 by defining a taxonomy for MR fidelity. The remaining questions are discussed in Section 3.2, by evaluating how fidelity can characterised.

3.1. Classifying Fidelity

The authors hypothesise that a more complete method to describe the fidelity of a prototype is to decompose 'fidelity' into its constituents. For this, the components proposed by (Fink and Shriver, 1978) are used: *Physical*, *Functional* and *Psychological*.

3.1.1. Physical Fidelity

Physical fidelity comprises of two main categories: *visual* and *haptic*.
To identify the dimensions of visual fidelity, the components proposed by (Milgram and Kishino, 1994) have been used: colour depth, screen resolution, refresh rate, quality of shading / texture / transparency and ray-tracing.
Haptic sensing in humans is an active process requiring movement and feedback to discover information about an object or surface. Analysis of this process has uncovered a set of exploratory procedures used by humans to determine various features about an object (Lederman and Klatzky, 1987) These are listed in Table 2 and can be used as a guide to identify the key components of haptic fidelity.

Table 2. Haptic Exploratory Procedures - from (Lederman and Klatzky, 1987)

Exploratory Procedure	Property Investigated	Methodology
Lateral Motion	Surface Texture	Skin moved laterally over the object's surface
Pressure	Hardness/ Compliance	Force exerted on the object (pressing, bending & twisting)
Static Contact	Temperature	Skin held to the surface of the object
Enclosure	Global Shape / Volume	Hand and fingers enclose around an object
Contour Following	Exact Shape	Skin contact following the gradient of a surface or edge
Unsupported Holding	Mass Properties	Object is held in the hand, without external support

3.1.2. Functional Fidelity

The functional fidelity of a prototype measures how well the prototype replicates the product's operation and its intended working environment. For example, a prototype drill could look and feel exactly like the final product, but without a trigger that causes the chuck to rotate and create representative noise and vibration, and the ability to drill a hole, then one could consider it to have low functional fidelity.

This can also be used to describe the depth in which a task or function is emulated in a prototype. For example, if prototyping the assembly process of a car, each assembly step could be represented within a digital environment by simply snapping parts together, or the full manual task could be simulated.

Functional fidelity can be broken down into operational, and environmental fidelity:

- Operational - Are the user interactions with the prototype representative to the intended design?
    - Inputs - Can you interact with the prototype as you would the final product?
    - Outputs - Does the prototype react to inputs as they would in the final product?
- Environmental - Does interaction with the prototype accurately represent interactions of the final product in its intended working environment?
    - Does the prototype act within virtual environment as it should, according to real world physics? Also referred to as construct validity by some[1] (Harris et al., 2021).
    - Are expected tasks for the prototype simulated?
    - Are these tasks simplified or fully representative?
    - Are stimuli that are present in the operational environment simulated?

3.1.3. *Psychological Fidelity*

Psychological fidelity is defined as the extent to which the user perceives the prototype as the final product, and whether they behave and act the same way as they would with the real product. It is heavily dependent on the physical and functional components of fidelity, and how they are perceived by the user. In order to achieve significant levels of psychological fidelity, the prototype must have high levels of both physical and functional fidelity (Ranney, 2011).

If the psychological fidelity is sufficient, a user's interactions should be representative of those in a real environment. This is not an easy task, as explained by (Ranney, 2011) on the subject of driving simulators. As there is no risk or danger, people drive with less care, and the lack of context associated to the driving task (Is the driver late for work? Do they have passengers?) often changes driving style. To address these behavioural differences, the participant should feel as if they are in the real scenario.

Two key characteristics of virtual environments will affect this: *Agency* and *Presence* (Piccione, Collett and De Foe, 2019). *Agency* is the extent to which a user feels ownership of a virtual avatar and its actions. This is driven by the ability to interact with the virtual world as they would the real world. *Presence* is the amount that a user believes they are really *in* the virtual environment. This is affected by the tracking, latency, persistence, resolution and optics of the VR or MR equipment (Iribe, 2014).

3.1.4. *A Taxonomy of Fidelity*

Based on the discussion in Sections 3.1.1-3.1.3, a taxonomy of different components of fidelity is proposed[2] and shown in Figure 3. This taxonomy is broken into three dimensions Physical, Functional and Psychological. Within physical fidelity, the different ways in which humans see and feel are decomposed. Within functional fidelity, aspects of interactivity and task realism are broken down.

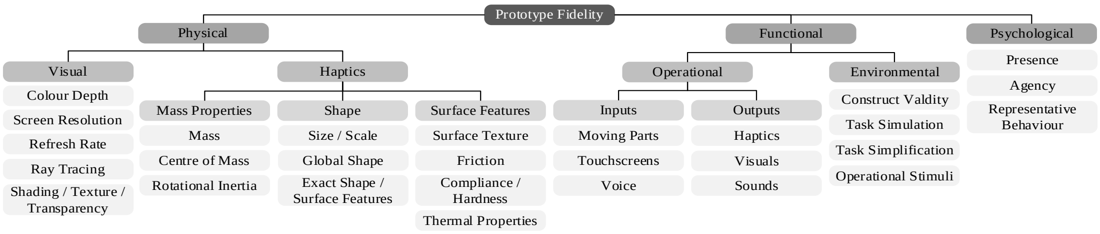


Figure 3. Proposed taxonomy of the components of prototype fidelity

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[1] It is worth clarifying that *construct validity* pertains to how well the prototype follows the laws of physics, such as Newton's laws of Motion. The *operational fidelity* covers how well the prototype responds to user inputs

[2] Shape is listed under both 'visual' and 'haptics', as due to the nature of MR prototypes, a prototype can have a different fidelity for the visually and the haptically perceived shape of the prototype.

Psychological fidelity is a more subjective dimension, assessing how representative the behaviour of the participant is. Other than the functional and physical components of fidelity, the main factors affecting this are presence and behaviour, so these are also listed in the taxonomy.

3.2. Characterising Fidelity

Having identified the process by which individuals interpret a prototype and the parameters that influence the interpretation, this section discusses how some metrics might be put to these parameters, such that they could be varied and/or used as a means to classify the fidelity of a prototype.

At the highest level of abstraction, prototyping literature often refers to prototypes as either high or low fidelity (Ulrich and Eppinger, 2015; Camburn et al., 2017). These descriptions are relative to each other and to the ultimate product realisation, and do not always provide meaningful detail.

It is proposed that fidelity can be quantified on a spectrum from 'null fidelity' to a perfect replica. An example of a 'null' fidelity, where there is no representation of a specific dimension of fidelity, would be of the haptics within a purely virtual prototype. As there are no haptic stimuli, the haptic fidelity can be assumed to be null. It is worth mentioning that not all dimensions of fidelity can be null. For example, the visual shape of a prototype will always be present in a physical, virtual, or mixed reality prototype, and therefore the fidelity can be very low but not null. A perfect replica would be at the maximum possible fidelity, as any further change will deviate from ultimate product realisation.

Describing the spectrum of fidelity between these two extremes is non-trivial and it could be either continuous or discrete. For example, the mass fidelity of a prototype could be expressed as the (continuous) ratio of the prototype's mass to the designed product's. Contrastingly, the fidelity of colour could be broken down into discrete levels: single generic colour, primary colours, correct colour codes. This latter example highlights another difficulty in defining the fidelity spectrum for each dimension of fidelity, as the colour fidelity could instead be assessed by comparing the accuracy of each RGB value. While both methods are valid, the latter option will not provide much meaningful information, and it may be that a third option is more valuable, or that different methods suit different problem contexts.

When creating a prototype, a common objective is to minimise cost and development time, which is often achieved by reducing the fidelity of a prototype. Therefore, by knowing exactly what level and dimensions of fidelity are required, prototypes can be made as lean as possible, providing required value with minimal development costs.

However, fully characterising how each dimension of fidelity can vary, and how it can be measured, is a non-trivial and significant task. Similarly, creating a full mapping of every different type of prototype and prototyping scenario to what level of fidelity is best suited is also non-trivial and would be a mammoth undertaking. As such, a methodology that allows the required fidelity to be characterised on a situational and contextual basis would be a more pragmatic and achievable option.

In order to characterise the required fidelity for a prototype, several considerations must be made:

Prototype purpose - What the designer wants to learn from the prototype. As defined by (Camburn et al., 2017), this could be Refinement, Communication, Exploration or Active Learning.

Prototype evaluation - How will the prototype be interacted with, will it be held, pushed, looked at, how much force will be applied, etc? What tasks will this product be used for? Who will evaluate the prototype - the designer, consumer, or another stakeholder?

Class of product - What type of product is it? What are its characteristics, luxury, cheap, practical, etc?

Design stage / Definition level - How much is the design defined? How much variation is possible?

External Constraints - Are there time and funding limits, and what fabrication methods are available?

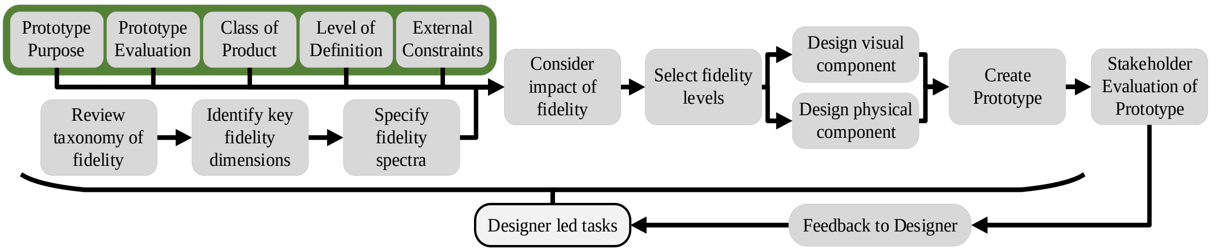

Figure 4. Summary of Prototype Fidelity Characterisation Process

Based on these considerations, the process shown in Figure 4 should be followed. First, the taxonomy of fidelity should be reviewed by the designer, to refresh their understanding of the different dimensions of fidelity. Following this, the key dimensions of fidelity should be identified, these will be based on the problem and situational context. For each of these key dimensions of fidelity identified, the fidelity spectrum should be specified, relative to the ultimate product realisation, or the 'as designed'. Based on the considerations stated above, suitable levels of fidelity should be selected for each key dimension, within the specified range. The final steps led by the designer are to specify the physical and virtual components of the prototype so that the prototype evaluator perceives the desired level of fidelity, and then to create the prototype. At this stage, the prototype should be evaluated by the relevant stakeholder. This is the point that the perceived fidelity can be checked against the specified fidelity, and the level of psychological fidelity can be verified. The feedback from this evaluation should then be given to the designer to verify and iterate the design.

3.3. Perceived vs. Actual Fidelity

As stated in Section 3.2, one of the last steps in characterising the fidelity of a MR prototype is to design the physical and virtual components of the prototype to achieve the desired level of fidelity. This step is non-trivial, as there has been research to show that when given contradictory visual and haptic information, the visual information will dominate. Therefore, the brain can be tricked into perceiving a different haptic stimulus that do not replicate reality. This effect has already been trialled in prototyping scenarios for haptic retargeting (Azmandian et al., 2016) and redirected walking (Razzaque, 2005).

As such, this effect should be considered when deciding on what levels of fidelity to employ for both the virtual and physical components of the prototype, as a low fidelity physical model could be perceived as a higher fidelity if the visual component is correctly created.

4. Evaluating MR Prototyping Tools

This section evaluates the fidelity of three MR prototyping tools to demonstrate the utility of the taxonomy. The selected tools are used to plan the furniture layout of a room or lab (Figure 5). However, different implementations led to varying fidelity levels, which can be characterised by the taxonomy.

a) (Janusz, 2019) - Design3R Interior design tool.

b) (Maurya et al., 2019) - MR furniture organisation tool

c) (Kent, 2021)- OurLab Lab equipment organisation tool

Figure 5. Examples of MR interior decoration / organisation tools

The first tool (Figure 5a) used a VR Head Mounted Display (HMD) system to place virtual pieces of furniture in the physical room that the user is in, allowing them to be viewed in-situ without needing any physical objects. Using the taxonomy proposed in Section 3.1, the dimensions of fidelity of this tool can be assessed. In terms of physical fidelity, the visual components of this prototype are high fidelity, with accurate colouring, shape, and positioning. The haptic component however is not considered (i.e., null).

In terms of functional fidelity, there is no operational interactivity with the designed room, and the context of exploring the room is not the same as if using the room on a day-to-day basis, with only bare furniture and no further human elements or other operational stimuli. However, the visual elements of the simulation behave as they would in real life, so the construct validation is correct in this sense.

In terms of the psychological fidelity, the use of high-fidelity visuals and the use of room-scale VR boosts presence within the scene, but no virtual avatar reduces agency and the lack of functional fidelity means that there is no scenario context which will change the user's behaviour and cognitive load from that in normal operation. Unfortunately, no user feedback was available for this tool.

The second tool, shown in Figure 5b, also uses a VR HMD, and is designed to help end-users plan the interior design of a bedroom. The top-down room view and use of position tracked 3D printed furniture models allow the users to arrange the virtual pieces of furniture rendered in VR. In terms of the fidelity taxonomy, the physical fidelity has clearly represented visuals (though not photorealistic) and the use of correctly shaped substitute models shows attention to the overall shape within the haptics component. However, all other aspects of the haptics are low fidelity.

In terms of the functional fidelity, while the room can be modified and reorganised, it cannot be interacted with as it would be in real life, resulting in a low operational fidelity. The lack of real interaction tasks and operational stimuli means that the environmental component is also low fidelity.

Considering the psychological fidelity, the top-down view removes any presence within the room and will completely change the behaviour of the user, compared to when they are in the room itself. The lack of a virtual avatar meant that the agency of the tool is low, and user feedback highlighted this (Maurya et al., 2019). However, user feedback also showed that the tool was efficient in carrying out the design task, as the high fidelity visual component of the tool was deemed the most important aspect.

The final tool, shown in Figure 5c, is similar in operation to the second tool, though instead of 3D printed models of furniture components, simple wooden cubes are used to represent furniture. This tool also uses intelligent design constraint information to continually guide the designer throughout the prototyping process, ensuring they are aware of the operational stimuli within the lab.

Characterising the fidelity according to the taxonomy, within the physical fidelity, the visual components are clearly representative of reality but lack detailed colouring and lighting. The haptic components are low fidelity, with non-representative shape, scale and surface features.

For the functional fidelity, there is no representative interaction with the lab environment, so the operational component has low fidelity. However, as the designer is continually reminded of the operational stimuli present within the lab setting through the design constraint information, which boosts the environmental fidelity. User feedback showed that this higher level of environmental fidelity helped to keep the design task grounded to the requirements, leading to a highly effective design tool.

In terms of the psychological fidelity, the top-down view reduces presence, but simulated hands increase agency. The consideration of the operational stimuli means that the cognitive state whilst designing will be closer to being representative, but the lack of immersion in the actual operational environment means that there is room for improvement in this dimension.

A summary of the fidelity profiles of these different tools is given in Table 3, where fidelity is quantified relative to the other models and to the real scene.

Table 3. MR Prototyping Tools and their Fidelity

Fidelity Dimension		Tool 1	Tool 2	Tool 3
Physical	*Visual*	Very High	High	Medium
	Haptic	Null	Low	Very Low
Functional	*Operational*	Null	Low	Low
	Environmental	Low	Low	Medium
Psychological		Medium	Low	Medium

Based on this breakdown, some insight can be gained. Tools 2 and 3 have the advantage of greater visibility of the whole room, but this comes at the cost of presence within the room, so design choices may lack appropriate consideration for the psychological fidelity. An improvement may be to include the option to explore the room at room-scale to verify and iterate choices made in the top-down view.

While the first tool lacked any haptic fidelity, this choice keeps the cost of the tool down, whilst keeping versatility high. This is a good example of where external constraints affect the suitable fidelity.

When creating a prototype, some dimensions of fidelity may be higher than needed. An example of this is the 3D printed furniture in the second tool. As proven using basic wooden cubes in the OurLab tool, accurate shapes for components that have been scaled down so significantly may be unnecessary.

Based on these case studies, we see that some choices in fidelity level are not fully informed and as such, some dimensions are not sufficiently representative, and some dimensions are overdone. Using the methodology proposed in Section 3.2 will add value to the design process as it will limit these errors.

5. Discussion of Opportunities and Challenges for MR Prototypes

By decomposing the constituent components of fidelity and proposing a method for evaluating this information during prototype development, several benefits for prototyping practice are asserted. By identifying clear targets for prototype fidelity, prototypes can be made more purposefully and evidence-based, with less time and resources wasted, due to a leaner production strategy. Also, a clear lexicon surrounding the components of fidelity will make it easier for prototype evaluators to verbalise thoughts on prototype performance and will therefore help reduce miscommunication.

Having identified the key dimensions of fidelity using the proposed taxonomy, further work is required to identify the best methods to quantify fidelity. These could be subjective or objective, and numerical or categorised. It would also be beneficial to devise methods of summing or combining different dimensions of fidelity, to give a general indication of the overall fidelity, such as a radar plot. With further work characterising the effects of different dimensions of fidelity on prototype performance and impression, it will also be easier to filter through and interpret feedback on a prototype to remove feedback pertaining to dimensions of fidelity neglected in that prototype, helping to quickly identify feedback that is helpful to meet the objective of that prototype.

An MR specific opportunity identified is the use of the virtual component to ‘upgrade’ the perceived fidelity of the physical component. This could reduce the required fidelity of the physical component of the MR prototype, reducing development costs and fabrication time. This technique could also allow rapid design iteration of MR prototypes, as small changes in the virtual model may not need to be represented in the physical artefact, but the change may still be perceived.

However, this technique is still largely uncharacterised with most work in this space being ad-hoc and only limited to a specific application. Further work is required to determine the limits of this phenomenon, and to verify its use in simplifying prototype development without decreasing perceived reality. Beyond this, we can start to experiment with combinations of physical and digital fidelities and how it supports/hinders the feedback provided by stakeholders interacting with the prototype. After this, it will be necessary to create some guidelines on how this technique can be used to maximise value.

As well as the further work required to investigate the disconnect between the real and perceived fidelity of MR prototypes, a significant challenge for design researchers in this space is to further characterise the relationship between different levels and dimensions of fidelity, and different problems and scenarios within prototyping. While characterising the required fidelity for every scenario, context and product class is an almost infinite task, common prototyping scenarios should be assessed to give general advice and provide examples for designers to use when selecting prototype fidelity levels.

Another challenge for design engineers is to further characterise the relationship between psychological fidelity, functional fidelity and physical fidelity, to better predict what levels of physical and functional fidelity are required for satisfactory psychological fidelity.

6. Conclusion

Prototyping is an essential activity in the design process. The activity requires designers to take the product definition - at a point in time (as designed) - and replicate it as a physical, virtual or Mixed Reality (MR) object that is potentially situated in its operating environment or abstraction thereof. Thus, the prototyping process is laden with assumptions, abstractions and in some cases, disregard to elements of the design of the prototype that ultimately impacts fidelity and its ability to reflect the designer's intent. The advent of MR is increasing both the complexity and opportunities of this process as it provides even greater configurability and ability to manipulate fidelity.

To unpack fidelity, this paper has worked through the ways in which prototypes are perceived and evaluated to identify the different dimensions of fidelity. Through this taxonomy of fidelity, designers are better able to characterise fidelity of prototypes. This will in turn support the purposeful and evidence-based decision-making that leads to a prototype being the prototype it is and will ensure that the prototype is accepted by the stakeholder and provide the best opportunity for the stakeholder to provide needed for the design process.

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