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MIXED REALITY PROTOTYPING: SYNCHRONICITY AND ITS IMPACT ON A DESIGN WORKFLOW

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ABSTRACT

Design is multi-modal, and depending on the current stage in the process, progress can be facilitated through working in either the physical or virtual domain with frequent iterations commonly required between. Traditionally, prototyping workflows are sequential, although current trends such as Digital Twinning and Mixed Reality (MR) enable decreased domain transition times, reducing the cycle time. This leads towards fully integrated digital-physical prototypes, enabling work in both domains simultaneously by increasing synchronicity of select variables. This paper considers those variables involved, the sensors that measure them and their rate of synchronisation, thereby investigating the feasibility of MR workflow interventions, and exploring the benefits that may be realised. The paper identifies four components of MR implementations in prototyping and myriad methods by which domain transition may occur and uses these in context of a case study to propose four levels of workflow synchronisation. It was found achieving some high rates of synchronicity is possible, but achieving the highest levels as prescribed by digital twinning is neither feasible nor pragmatic against current MR capabilities and design prototyping workflows.

Keywords: Virtual reality, Integrated product development, Virtual Engineering (VE), Mixed Reality, Prototyping

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1 INTRODUCTION

The advantages of prototyping are demonstrable and measurable, with prototyping being a core element of many design process models. There is compelling evidence that prototyping, when used effectively, has a significant positive impact on the success of a design project (Camburn *et al.*, 2017). Prototypes are embodiments of concepts and can fulfil a range of purposes, acting to support exploration, to improve potential solutions, to facilitate communication, and to record the development process (Ulrich *et al.*, 2012). There is a significant body of design research looking to understand, rationalise and capture the essence of prototypes to inform best practice when determining their use.

The prototype itself is an artefact that can exist either virtually or physically, with each form providing advantages and limitations. The advantages of the physical domain, such as tangibility and unambiguous representation (Donati *et al.*, 2015), do not translate to the virtual domain and likewise, the advantages of virtual prototypes remain similarly confined (Wang *et al.*, 2002). Prototypes existing in one domain are generally not interoperable with prototypes in the other. For example, a physical change to a 3D printed artefact will not affect its corresponding CAD model without manual intervention, nor will editing the CNC instructions have any immediate effect on the physical artefact without a realisation process. Any design process will generally include iterations of prototypes in both domains, as different dimensions of interest are probed, with a non-zero domain transition cost.

In the majority of engineering design workflows, these iterations typically fall sequentially, with changes in one domain requiring an (often manual) update process to the corresponding prototype in the other. This results in an inherent inefficiency caused by this domain transition, both in terms of the time/cost and resource of synchronising models, the lost learning time with additional integration time, and potential new errors introduced to the process by the system.

1.1 Value of an integrated workflow

A paradigm gaining momentum, and one which may help scaffold the model of mixed reality prototyping, is the digital twin. A digital twin can be described as a physical entity, a virtual counterpart, and the data connections between them, providing a wide range of capabilities, with applications and perceived benefits being studied across the design process (Jones *et al.*, 2020). By achieving higher rates of synchronisation, one end goal of this trend with respect to prototyping is in the full integration of workflow across physical and digital domains, such that the transition cost between each is all but eliminated. One recently maturing technology by which this paradigm could be realised is that of Mixed Reality (MR), in which virtual artefacts are superimposed onto our physical domain, and actions in our physical domain are rapidly digitised and presented back. The premise of value therein is that synchronisation between physical and digital domains allows decreased design cycle time, while simultaneously enabling new capabilities for rapid analysis and realisation of designs with full traceability. However, to date there is little understanding of the way in which MR technologies can and should be implemented in a design and prototyping context to best support design activity, and to explore and create integrated workflows. Endeavouring to create a digital twin in the earlier stages of design, where requirements are unclear and concepts even less so, has been shown to have value (Jones *et al.*, 2019) but there is still significant scope to explore.

With the existence of a wide variety of physical and digital prototyping methods (Coutts *et al.*, 2019; Mathias *et al.*, 2018), each offering well-established value propositions and affordances, the challenge of synchronisation of physical and digital models in design can be considered to concern the 'data connections between models', or the way in which such extant methods may be aligned and synchronised. Mixed Reality, as a facilitator of these data connections, brings a host of complex implementation challenges, requiring interoperable hardware and software working in sync. This paper explores the capabilities and opportunities afforded by MR technologies, guided by the following research questions:

1. What can be measured and mapped across the physical and virtual domains?
2. How does parameter synchronicity impact a design prototyping workflow?

In answer to these questions, a review of a range of characterisations of mixed reality and the components of a prototype is conducted, with a thematic analysis to determine the key components of a mixed reality system. These themes are used to posit a series of measurable parameters and defining

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characteristics. In this paper, these will be referred to as *Inter-Domain Characteristics* or IDCs and are defined as *the characteristics and measurable parameters that can be represented in both or either of the physical and the virtual domains*. How these parameters can be measured, captured, or represented are then considered, and the inherent domain transition cost of moving from virtual to physical or vice versa. Synchronisation options are then presented in context of a design prototyping activity.

2 MIXED REALITY TECHNOLOGIES IN PROTOTYPING

Mixed reality is the superimposition of the virtual onto the physical domain through a range of sensors, algorithms, interfaces and displays. To superimpose onto the physical domain, the physical must be measured, localised, and interpreted to ensure the virtual remains accurately 'anchored' to the physical, with consideration of physical model geometry and motion.

As the capability of technology increases in tandem with our understanding of what comprises mixed reality, scholars have published a range of classifications, characterisations, and taxonomies to attempt to unravel and elucidate the complex interfaces and interrelationships between the digital and physical. These take a range of perspectives and framings (see Table 1) in how MR technologies bound and bridge these domains. Through these framings, it is possible to understand what is possible and begin to extract MR implementation good practices.

- **Displays, the environment, and you:** One of the more commonly cited mixed reality classifications, Milgram *et al.* (1995) introduce the widely accepted reality-virtuality continuum, in which mixed reality enabling displays fits on bound scale from the entirely physical to the entirely virtual. This continuum is extended to a three-dimensional taxonomy comprising three dimensions: extent of world knowledge, reproduction fidelity, and extent of presence, motivated by the display options and capabilities. Roo *et al.* (2017) build on this taxonomy and integrate the user as an entity that also can be coupled or decoupled with the virtual domain, enabling multiple mixed reality modalities to coexist in single platforms. For prototyping, the intended user or user proxy and measuring how they interact with or interpret a design is of interest when conducting usability studies. Verlinden *et al.* (2006) considers the technologies that comprise display technologies, physical model creation, object tracking and user input, and how they enable functional augmented prototypes, mapped against specific product scenarios, provides an excellent foundation, albeit with a limited scope of scenarios and extant technologies.
- **Starting with the object:** Several of the posited divisions lead the framing with the physical component, its properties, capabilities, and the interface it has, if any, with the virtual. Fitzmaurice *et al.* (1995) looked to classify the features and parameters that comprise a graspable user interface. Each graspable user interface is considered to be space-multiplexed and time-multiplexed, in that each interface either does one thing, or it can be utilised for a range of functions. This classifies a mixed reality prototype by its final state, not as part of a learning or communication exercise typically associated with design. Aoyama *et al.* (2009) propose hybrid models, in which there is a physical and virtual component to a prototype and is used to evaluate a design. Information flow and sensors used are presented, but with little to no discussion as to whether this is appropriate for the stage in the prototyping process. Anthes *et al.* (2016) look to classify input and output devices that could comprise a real time mixed reality system. This is posed in the context of comparing commercial headsets, peripherals and capabilities, therefore providing a contemporary review of what can be captured and synchronised between the physical and virtual. Schleich *et al.* (2017) uses the context of the digital twin to find aligning properties between the digital and physical and how to measure and clarify the likeness between the two.
- **Remembering the design context:** There is also work being done by the design research community, considering mixed reality against the design process and the value proposition for designers and design researchers. Barbieri *et al.* (2013) propose a range of mixed reality driven usability tests for prototypes, indicating the fidelity of mixed reality prototypes for each stage in the design process, with an example series of studies. According to Barbieri *et al.* (2013) mixed prototypes are feasible from detailed design, although Giunta *et al.* (2018) shows there is research addressing the earlier design stages of concept and preliminary layout, indicating a value proposition for designers earlier in the design process. Giunta *et al.* (2018) also looks to identify what may be the determining factors in the application gaps, citing a lack of perceived added value and earlier stages requiring

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less visualisation to understand. Maurya *et al.* (2018) posits design modification time as a driver for mixed reality prototypes, alluding to the significance of synchronisation time as an important factor in determining the fidelity of the physical and virtual. A particular case, and one which lies close the paper topic, is the implementation of the design prototype capture tool 'Protobooth'. In this project, the design researchers deem the four most important dimensions of a prototype to capture for research purposes are the physical appearance, the designer's intent/driving questions, who participated in the realisation of the prototype and when the prototype was built Erichsen *et al.* (2020). The first category, capturing the shape, appearance and materials comprising the prototype provides a series of challenges for mixed reality, whilst the rest of the categories can be considered prototype metadata, indicating information about the prototype in the wider context of the design process.

Each of the above has taken a distinct perspective on how to characterise and frame the bounds between the virtual and physical, and the characteristics or features that enable mixed reality. Some have considered the implications for designers and the design process, but to date, there are none that have looked to identify what can be synchronised across domains as part of a design prototyping activity, from a technical capability perspective. The next section will look to explore this proposition further, with the aim of synthesising a new frame of reference concerning the inter-domain bridging characteristics that a prototype can have.

3 SYNTHESISING A CHARACTERISATION

Aligning with the breadth in Mixed Reality (MR) technologies and applications as discussed in Section 2, there are a multitude of potential prototype parameters that can be measured and mapped across the physical and virtual boundaries. With little framing of MR applications in prototyping covered in extant design-focused literature, this section elicits these parameters through a systematic literature review process of MR to identify and collate relevant literature, followed by a thematic analysis. Performing a thematic analysis Maguire *et al.* (2017) involves six phases: (i) data familiarisation; (ii) generate initial codes; (iii) search for themes; (iv) review themes; (v) define themes; and, (vi) write-up. This paper(vi), presents the output from this non-linear and iterative process. Table 1 presents the output of (i) and (ii), Figure 1 shows the output of iii and iv, and Table 2 summarising (v).

3.1 Review Process

Data familiarisation (i): The relevant publications were found through searches of the Design Society publication library and Google Scholar, using permutations of the key words mixed, augmented, reality, prototyping. 10 relevant papers were identified. A publication was deemed relevant if it has attempted to describe or characterise an element of mixed reality in the context of physical and virtual elements. These come from a range of journal and conference series, implying a lack of a specific publication or specific and established community of researchers working in this field.

Form initial codes (ii) and search for themes (iii): Defining potential measurable Inter-Domain Characteristics (IDC) is achieved by identifying the terms used in the paper that the authors deemed to be defining characteristics of bridging the physical and virtual domains. The constituent elements of those characteristics are then distilled. For example, Milgram *et al.* (1995) gives a category as extent of world knowledge, encompassing the fidelity to which the environment is captured, modelled and the extent to which the capture of the environment is understood by the mixed reality system. The domain bridging characteristic is that the environment is captured and interpreted, Table 1, and can be achieved through a variety of methods as shown in Table 3. A photograph can be a near instant, realistic capture, but has no geometry unless combined with latency inducing computer vision algorithms enabling complex capabilities such as Simultaneous Localisation and Mapping (SLAM) or object recognition. A method with a far slower in terms of synchronisation time, than using CAD software to produce a 3D model of the environment.

Review (iv) and define (v) themes: Four components emerged as having mixed reality facilitated IDCs, shown in Figure 1. These have been extracted from literature through finding the themes in column 4 of Table 1. This has taken elements from each of the publications, and framings within the core context of MR-facilitated prototyping. Unlike many of the previous groupings identified in Table 1, to be able to cycle between the physical and virtual, a *physical prototype* must exist to be measured and

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captured. This is the object of interest and its existence provides context for the prototyping activity. This physical prototype must also be localised in space, relative to the cameras, the user, and any other objects, all requiring the *environment* to be captured and interpreted to some degree. The system will not exist in isolation and require a *user*, an operator or group in which to experience and interact with the physical prototype and the environment, with these interactions requiring capture and responses. Finally, *metadata* captures the metadata of the prototyping activity such as when it occurs, the design rationale and process information. Figure 1 indicates a proposed model and how these components are independent of each other, but each interface with the mixed reality system, with Table 2 summarising each component. There is no clear system architecture for what constitutes a mixed reality system, only definitions requiring some blending of the physical and virtual. At a minimum, a mixed reality system must process, store and manage the information, in this case the virtual prototype, and display through superimposition of the virtual into the physical domain.

Table 1. Determining inter-domain characteristics

Publication	Relevant Terms	Description	Inter-Domain Characteristics (IDC)
(Milgram *et al.* , 1995)	Extent of world knowledge; Reproduction fidelity ; Extent of presence	A measure of much of the environment is measured and how well it is understood. ; The quality of the intended objects to be displayed virtually.; How immersive is the experience for the user? ; Is the implementation for them or are they an observer?	Orientation and dimensions of object relative to display; Modelled environment; Environment capture and understanding; Physical/virtual objects/environment; User tracking; User input
(Roo *et al.* , 2017)	Physical world; Augmented surfaces; Mid-air digital content; Object decoupling; Body decoupling; Virtual world	Scale from everything fully physical, superimposing virtual over and around the object, decoupling the world around the user, decoupling the user, everything fully digital.	Physical object in space; The environment; The user; User input; User feedback
(Fitzmaurice *et al.* , 1995)	Internal ability; Input and Output; Spatially aware; Communication; Interaction time span; Number in use; Function assignment; Interactive representations; Bond between physical/ Virtual layers; Granularity; Surface type/ texture;	A characterisation of graspable user interfaces in terms of the physical objects' capabilities. Some of these are the physical characteristics, with the rest acting as interfaces, internally, to the user, and to other relevant entities.	Form; Sensor reading; Position and orientation; Audio; Temperature; Tactile; Visual; Function; User Interaction; Scale
(Verlinden *et al.* , 2006)	Model creation; Input – object tracking; Input – user input; Output (Display)	Defining possible technologies that could comprise an augmented prototype. They are considered as inputs and outputs of AR systems, and abilities of physical model making.	Displays their interface, capabilities, coverage, and resolution.; Object tracking; Sensor reading; Hand tracking
(Aoyama *et al.* , 2009)	Head mount display; Real (physical) Model; Operators Hands; Virtual CAD model	The virtual components that make up a hybrid model, emulating to augment a physical component.; A measurable user interface is also required to evaluate the designability and operability.	3D model, ID, shape; number, colour, material; absolute position ; relative position; child objects.; Operators hand tracking, input methods.
(Barbieri *et al.* , 2013)	Degree of flexibility; Touch realism; Conceptual Design – low fidelity prototype; Detailed design – virtual prototype; Design evaluation – Mixed prototype with flexible archetype; Final design evaluation – Mixed prototype with physical mock-up; Design approval – fully operational prototype	Flexibility in terms of the systems capability to be edited to suit the needs of designers.; Touch realism in terms of the fidelity of the tangible feedback. ; Mixed domain prototype only integrated during detailed design evaluation.	Hand tracking; HMD; Speaker system; Relative position ; Integrated sensors; Input communication; Hand tracking; Sound rendering; Tangible inputs
(Anthes *et al.* , 2016)	Output – Visual / Haptic / Multisensory; Input – Controller / Navigation Devices / Tracking hand/body	A taxonomy of contemporary mixed reality technologies, split into input and output, generated through consideration of existing consumer mixed reality products.	Display systems; Person/object tracking; Wind in/out; Olfactory in/out; Audio in/out; Tactile in/out; Head/Body/Hand tracking; Input and control; Controller; Navigation devices
(Schleich *et al.* , 2017)	Scalability; Interoperability; Expansibility; Fidelity	A set dimensions in which to assess the closeness of a physical twin and a digital twin.	Form; Geometric variance
(Maurya *et al.* , 2018)	Level of Immersion; Level of Control; Design Modification Time; Level of Interaction	Two distinct scales, used in this context to highlight a research gap, but provides value when determining what is important from a design research perspective and enabling technologies.	Heart rate; Skin conductance; Hand tracking; Tangible User Interfaces; Object tracking; Audio Output
(Erichsen *et al.* , 2020)	Physical appearance and form; designer's intent/driving question(s); Who participated in building the prototype; When the prototype was built	In context of creating a prototype capture tool, able to collect data with minimal interruption.; A static single instance.	Form of prototype; Prototype metadata; Process metadata

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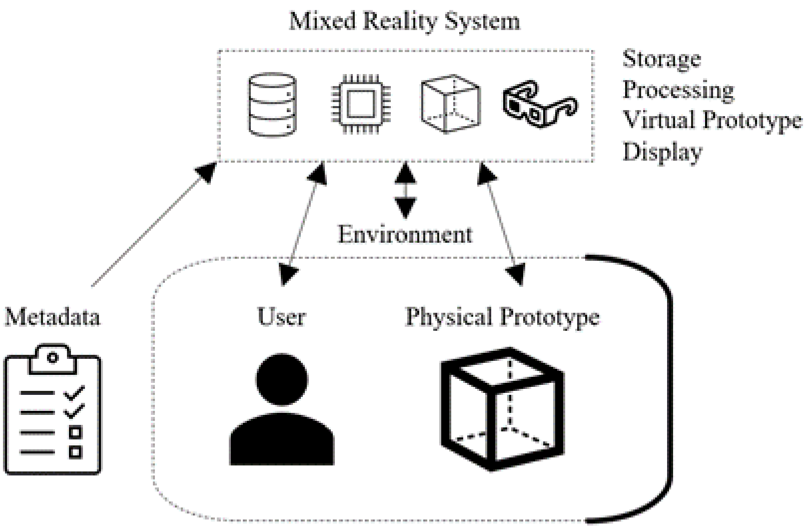

Figure 1. The components of a mixed reality prototyping system

4 RESULTS AND DISCUSSION

So far, and in answer to the first posed research question, we have identified the constituent components that can be facilitated by a Mixed Reality system (Table 2), with the inter-domain characteristics being the elements that make up each of those components. Following this identification of the key components, there is a vast array of Inter-Domain Characteristics (IDC) and ways in which these can be represented, many of which are presented in Table 3. These IDCs have been been been identified primarily through 1. Table 3 also presents what the components of the system are, some of their respective IDCs, and what are the sensors and processes enabling bidirectional domain transition. It is of note that Table 3 is not exhaustive and will continue to develop, and the table in tandem with this development. This can be used to support discussion of how the domain transition options and the associated sync speed can impact a design prototyping workflow.

Table 2. Defining components with inter-domain characteristics

Component	Description	Examples
Physical Prototype	The corporeal entity, a realisation of a concept that is an unambiguous representation and a tangible interface in which to interact with.	Rapid prototype Foam/Cardboard model Construction Kits
Environment	The environment and phenomena in which the Physical Prototype is subject to.	Room geometry Other physical objects
User	The individual or group operating and interacting with the prototype and the environment.	Designer Test participant Observer
Metadata	The data, information, context and performance of the system and the prototyping activity.	Current time Design rationale Prototype iteration
Mixed Reality System	The storage, processing, management of the virtual prototype, and display facilitating the mixed reality system for the user.	Mixed reality headsets Cameras Projectors

4.1 Synchronising what?

Table 3 aligns IDCs with potential virtual representations and options for domain transition. The physical components can be captured through a range of techniques and can be stored and represented in a variety of ways, with each of these methods having a non-zero domain transition cost; indicated by

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Table 3. Inter-domain characteristics, domain transition options and sync speed

Component	Inter-Domain Characteristics	Physical ->Virtual Domain transition options	Sync Speed	Virtual ->Physical Domain transition options	Sync Speed
Physical Prototype	Image	3D modelling	Slow	Human actuation	Slow
	Video	CAD tools	Slow	Conventional Machining	Slow
	3D model	Photogrammetry	Medium	Reshaping the object	Slow
	Textured model	Computer vision	Fast	Olfactory	Slow
	Rigged model	Camera	Fast	Additive Manufacture	Medium
	CAD reflection	Intrinsic Sensors	Fast	Subtractive Manufacture	Medium
	Digital Twin	Extrinsic Sensors	Fast	Actuators	Medium
	Local Position	Fiducial markers	Fast	Projection	Fast
	Relative Position	Inertial sensors	Fast	Stewart Platform	Fast
	Global Position	GPS	Fast	Augmented Reality object	Fast
User	None	Scribe	Slow	Olfactory	Medium
	Voice	Animation	Slow	Haptic	Fast
	Gaze	RFID	Medium	Audio	Fast
	Gesture	Microphone	Fast	Visual	Fast
	Motion Capture	Eye tracking	Fast	Functional	Fast
	Rigged Model	Hand tracking	Fast	Tangible	Fast
		Inertial tracking	Fast		
		Computer vision	Fast		
Environment	None	3D Modelling	Slow	Computer graphics	Slow
	Image	Photogrammetry	Medium	Human actuated	Medium
	Video	SLAM	Fast	Virtual Reality	Fast
	3D Model	Camera	Fast	Augmented Reality Object	Fast
	Point Cloud			Environment rendering	Fast
Metadata	Designer	Transcribe	Very Slow	As required	N/A
	Date	Text input	Slow	Augmented Reality Object	Fast
	Iteration number	Speech to text	Slow		
	Design rationale				
	Design intent				

synchronisation speed. The form also includes the location and rotation of the components. The newly updated virtual prototype can then be modified, and these modifications manifested in the physical domain. The table can be used to build on question 1, enabling designers and design researchers to understand the IDCs and these can be represented, captured, and their synchronisation speeds.

4.2 Impact on a Design Prototyping Workflow

To further understand parameter synchronicity and the potential impact to a design workflow, a use case is considered against a set of synchronisation rate options. This use case provides illustration to contextualise the use of MR, and will expand and detail the opportunities made available through the use of the technologies that have been identified in this paper, in particular in presenting the opportunity for integrated workflow that MR presents.

Case context and digital/physical design prototyping workflow: A designer is exploring the configuration of inputs for the controller, and has additively manufactured a prototype, derived from a CAD model. The designer wants to gather user input to ensure three buttons are placed in a comfortable position. Simultaneously, the designer must consider the technical impact and feasibility of button placement on controller internal packaging and internal requirements.

MR workflow and process options: This case is be considered against four MR workflow possibilities, each aligned with domain transition options of different synchronisation speeds (see Table 3. Each follows the generic prototyping process shown in Figure 2, which also indicates process integration at varying synchronisation rates. There are many IDCs that can be accounted for that will have significant impact on the prototyping activity and its output. To facilitate discussion, there are four possible implementations presented.

- **Traditional Iteration / No MR implementation:** A prototyping activity in which the virtual domain might be used later in the design process, as part of detailed design. User and usability studies are entirely tangibly driven, and the physical prototype exists purely physically to communicate as a boundary objects. The controller form is likely to be made of a low-fidelity medium such

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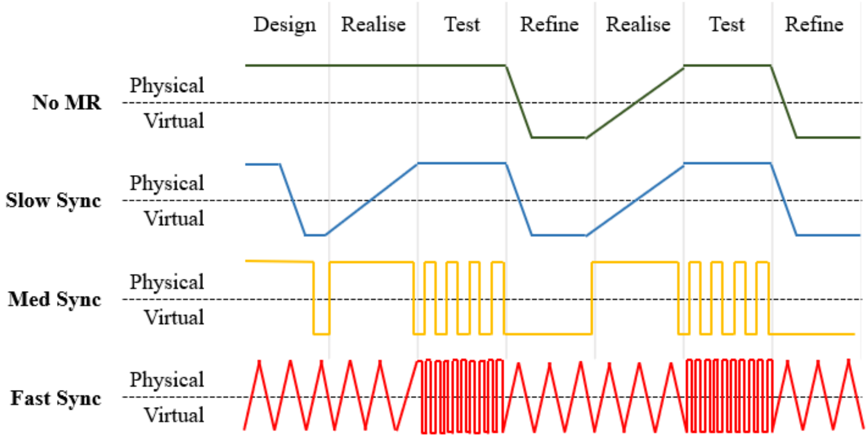

Figure 2. Design cycle indicating synchronisation rates

as clay or cardboard, and any changes posed by the user study participant will not be realised for testing until a future usability study. No leveraging of the benefits of integrated workflow occurs.

- **Slow IDC Synchronisation:** At this rate of synchronisation, relevant IDCs are able to move between the domains, but this is most likely human actuated and time consuming. These domain transfer methods take hours and days, not the sub-second timescales enabled by higher sync speed options. As an example, consider creating a CAD model that is then additively manufactured. A change to the model would require someone capable with the software and familiar with the design to make the change, which would then need to be re-manufactured. This implementation would not have a complete cycle in a single test as indicated by Figure 1, and depends on post-session processing of anything that is captured. Realisation methods, or the virtual to physical transition, are often the restrictive step that brings prototyping implementations into this group, in that manufacturing and manipulating the physical domain comes with significant and difficult-to-mitigate overhead. Using MR components may form one approach to overcome this by substituting physical elements with virtual representations, at the expense of tangible interaction.
- **Medium IDC Synchronisation:** By integrating MR technologies facilitating IDCs, a significant amount of information can be captured, enhancing the potential of a prototyping activity. In this case the controller and button positions are tracked in local 3D space. This enables the positions of the buttons to be quickly identified and located, and the corresponding constraint based model (upper-left of Figure 2) to be updated in as close to real-time as possible. The inputs are also being tracked using pressure sensors, allowing input of a configurable interface. The geometry is not scanned in this example, but could be if using photogrammetry hardware and techniques. Due to current geometry processing capabilities, real-time form capture of the shell of physical objects cannot be achieved at the speeds required by mixed reality. In this case, MR can ’fill the gaps’ in that any lengthy realisation processes can be substituted temporarily using anchored superimposed geometry, albeit without the benefits of tangibility. As such medium-sync IDCs give potential to substantially lower cycle time within prototyping, while simultaneously increasing real-time analytic capability. Many of the current innovations are happening in this space, as systems become more capable and interoperable. An example of this can be seen in Figure 3.
- **Fast IDC Synchronisation:** This could be seen as analogous, or certainly aspiring to be, the digital twin of the prototype. Any physical changes are reflected virtually, and any virtual changes are reflected physically in near real-time. The physical prototype and as many of its relevant characteristics can be measured and managed as a virtual prototype, and the designer may choose to proceed in either domain at will and according to needs of the task, with minimal transition time. In so doing, the designer may maximise strength of each domain in context of the prototyping process, e.g. maximising tangibility in user studies, while maximising analytic capability to ensure technical feasibility. The environment and user are also captured, with interoperable and responsive software. This stage is most likely not feasible with current technologies and limitations, and the challenges associated with implementation may currently outweigh the potential value.

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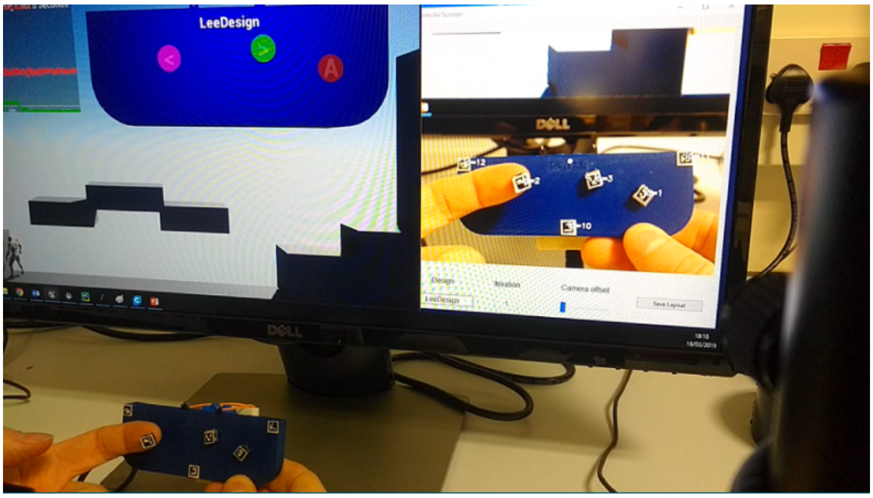

Figure 3. A medium IDC sync MR prototype implementation

Benefit of MR implementations: The use case illustrates the potential process improvements enabled by MR implementations through four levels, ranging from no synchronisation to near real-time. In line with recent work on early-stage digital twinning (Jones *et al.*, 2019), substantial value is implied by increased synchronisation, including reduced design cycle time, increased analytic capability, and maximisation of the benefits that each domain presents. Technological barriers remain however, preventing highest levels of synchronisation with current capability.

4.3 Future Work

This paper has taken the specific frame in identifying the relationship between synchronicity and design, but there are clearly many more factors at play. To maintain a feasible scope, these have deliberately not included as part of this discussion. Some of these factors include, the *fidelity* required of the virtual and physical prototypes, the *amount of information* already collated and how to retrieve it, the *bandwidth* afforded by the sensors, storage and raw processing power, upfront *implementation costs* of hardware, software and in building an interoperable virtual physical system, and finally the *error rate* and *error correction*. Beyond exploring the impact of these variables, there is an opportunity to utilise these results to facilitate the creation of mixed reality prototypes and systems with designers. This would provide an opportunity to understand motivators and inhibitors for increasing IDC synchronicity, challenges with implementation and the cost of mixed reality prototypes, as well as determining best practice.

5 CONCLUSION

In conclusion, this paper set out to explore the complex relationship between the physical and virtual domains, in context of design prototyping. By looking at a range of literature, it is clear that there is still a significant amount of discussion to be had in this space, and there is a large number of contributing factors. This paper took the frame of synchronisation and its role and impact to already complex and not fully understood design prototyping workflows, with the discussion guided by two research questions:

1. What can be measured and mapped across the physical and virtual domains?
2. How does parameter synchronicity impact a design prototyping workflow?

In answer to the first question, many Inter-Domain Characteristics were found, broadly fitting into four categories that are facilitated by a Mixed Reality System. These are the *physical prototype*, the *environment*, the *user*, and *metadata*, and are expanded in Section 3.1, Table 2. The parameters and bidirectional transition options are considered, from a technology viewpoint, and the inherent sync rates illustrated, show in Table 3. A use case is evaluated against four levels of synchronicity to deduce the impact to a design prototyping workflow. It was found achieving some high rates of synchronicity is possible, but substantial technological and workflow hurdles remain before the highest levels of synchronisation as prescribed by digital twinning may be achieved. Finally, it was found that integrated workflow via MR presents substantial potential for benefit, including in reduced cycle time and increased analytic capability that through future work, may be realised to support and streamline the design prototyping process.

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