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Integrated Physical-Digital Workflow in Prototyping – Inspirations from the Digital Twin

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Abstract

Prototyping uses many models over its process, with varying strength and weakness offered by those in the physical vs digital domains. Working across domains is necessary but introduces a transition cost, process complexities, and risks lost learning. Drawing from Digital Twinning, this work explores the creation of integrated physical-digital prototyping workflows, where technology enables simultaneous cross-domain working. It contrasts four case-study implementations of integrated prototyping workflow to current practice, exploring feasibility, value, and implementation challenges.

Keywords: prototyping, immersive technology, design tools, digital design, digital twinning

1. Introduction

Modern engineering design, and particularly design prototyping, requires both physical and digital tools and media. An orchestration of physical and digital entities are used to develop products (Ulrich and Eppinger, 2012), with prototypes, tests, and simulations used to develop understanding, support decision-making, and ultimately converge towards a single solution to put forwards into production. More recently, technological advances in digitalisation, human-computer interaction, sensing, and information management have created the opportunity to bridge the 'physical-digital divide'; the separation of the physical and digital domains. This rapidly expanding field is typified by the concept of Digital Twinning (Jones *et al.*, 2020) in which advances in multi-physics simulation and real-time sensing have allowed replication and synchronisation of the physical system with a digital counterpart and vice versa - blurring the divide between them and moving ever closer to a Cyber-Physical System. This paradigm has enabled new capabilities, accelerated decision-making processes, and generated value across the engineering sector. This concept of physical-to-and-from-digital synchronisation and the ability to work seamlessly across them gives rise to a possible future paradigm for engineering design workflows, in which close coupling of the two domains can be leveraged to benefit the design process and designed product as a whole; saving time, cost and improving quality.

However, while it proposes broad benefits, digital twinning itself has to-date been applied primarily in operational life-cycle phases for engineering systems only (i.e. automotive, aerospace, and production systems) with less focus on earlier phases of the design and development process (Jones *et al.*, 2020), including design prototyping. Here, both digital and physical models are critical design elements with individual strengths and weaknesses (see Section 2.1), with transition cost and complexity introduced by the need to maintain product evolutions across the domains as the design progresses, and with potential for emergent benefits to be introduced through closer domain coupling in line with the principles of digital twinning.

Further, while digital twinning research is generally considered to be a closed cycle of digital-to/from-physical synchronisation that should be maintained throughout operation (see Figurre.1), the engineering design workflow occurs longitudinally with many parallel activities and iterations, and the definitions of the physical and digital components co-evolve in full or part. Thus, in contrast to a Digital Twin of a production system, the creation, modification and interaction of the physical and digital domains in earlier process stages is nontrivial and context dependent. This includes how and when digital and physical entities are interacted with and generate value. With design prototyping comprising a multitude of partial, evolving and interrelated digital and physical representations, 'idealised' twinning - perfect and consistent bi-directional synchronisation of the digital and physical - is not viable. Rather, it is necessary to consider how entities in the physical and digital domains may be coupled such that the strengths of each are maximised, transition cost between domains is minimised, emergent benefits are realised, and rapidly and substantially changing models may be accommodated.

To explore this opportunity, this paper explores twinning-inspired integrated physical-digital workflow in engineering design prototyping with respect to (a) realising value from close coupling across domains in earlier design stages, and (b) forms of integrated physical-digital workflows that are tolerant of, and support, the evolution of product models. Through an exploration of four cases it frames integrated workflow, identifies challenges, and proposes value propositions to be developed in future work.

2. Background

2.1. Physical and Digital Prototyping

Prototyping is well-recognised as a critical part of the design process (Lauff *et al.*, 2018) with a range of purposes and value (Camburn *et al.*, 2017). The process of prototyping can be considered that of embodying a representation of a design or concept for purposes of learning, analysis, refinement, and communication (Camburn *et al.*, 2017), with prototypes then every instance of representation prior to the final product. Effective prototyping will positively impact design success but must be moderated within the bounds of acceptable time, cost, and implementation constraints of the wider design process using appropriate mediums and fidelities (Ulrich and Eppinger, 2012), with differing media producing knowledge at varying fidelities according to their type (Goudswaard *et al.*, 2021). Broadly speaking, Houde et al. (1997) propose that prototypes may be typed by *role* (testing how well the prototype completes the products function), by *implementation* (testing how the product works or behaves), and by *look/feel* (testing interaction with the product, including aesthetic, ergonomic, etc.). This gives rise to a continuum (see Figure.1) where prototypes may focus on any or some combination of these dimensions. In a typical design process it is often necessary to create prototypes that test dimensions in isolation and in combination, with a final prototype testing all simultaneously.

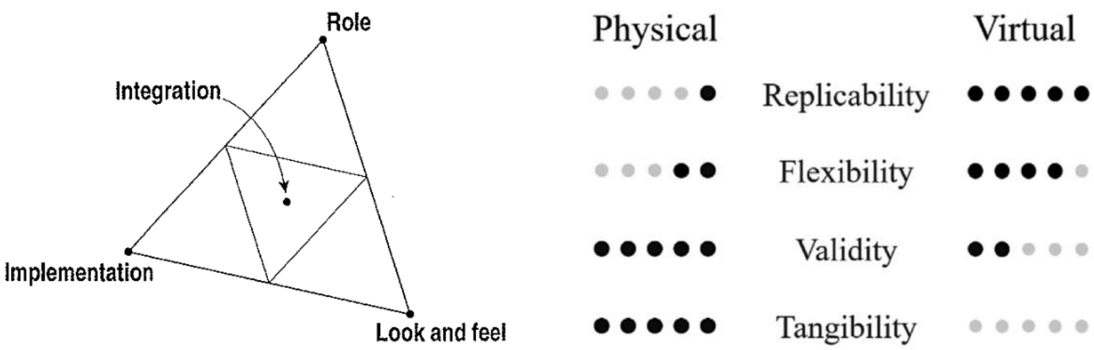

Figure 1. (L) Prototype types (Houde and Hill, 1997) (R) Relative strengths of physical and digital prototypes (Kent, Snider, Gopsill, *et al.*, 2021)

A wide variety of physical and digital prototypes are created within a typical design process (Ulrich and Eppinger, 2012) with those in each domain holding different strengths and weakness (Coutts et al., 2019; Liker and Pereira, 2018). Physical prototypes offer unambiguous form, tangibility, and direct perception and interaction with users, as well as real-world validation of role and implementation (Camburn et al.,

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2017; Liker and Pereira, 2018). Conversely, both fabrication time and cost can be high, compounded by a lack of flexibility of the final prototype form either to be edited and re-tested, or to be used for multiple purposes. Virtual prototypes (i.e., digital mock-ups, CAD models and simulations) offer a much higher degree of flexibility via quick and reconfigurable manipulation of form or parameters, allowing multiple versions to be created and tested rapidly. They also offer digital version control and quick digital sharing. Conversely, the physical properties that they emulate are challenging to represent in a way that is tangible to users and the software learning curve required for their generation is often large, creating complexity and increased realisation time (Kent, Snider and Hicks, 2021).

Inspecting prototypes across these domains it is interesting to note that many of their benefits and weaknesses lie counterpoint to each other - where one domain is weak, the other is strong (Kent *et al.*, 2021), see Figure.1. This raises two questions for effective working across domains - with both physical and digital prototypes being critical in design prototyping: **[1]** How can prototyping workflow be structured to maximise benefit and minimise cost? And, **[2]** can physical and digital prototyping be better integrated to simultaneously leverage the strengths of each?

2.2. Digital Twinning and physical-digital workflow

This concept has recently been demonstrated in the rapidly emerging field of Digital Twins (DTs), and Twinning. Formalised by Grieves (2014), twinning creates a real-time digital replicant of a physical system to as high fidelity as viable, which is then used to perform multi-physics (and other) simulations of system behaviour and performance. Outputs are used to understand, manipulate, and optimise the physical system, often automatically, creating learning/action loops that improve system performance. The sustained inter-connection between physical and digital versions of the system of interest has shown substantial value across suppliers, engineers, service-providers and users (Jones *et al.*, 2020), accelerating operational processes and increasing access to information with reduced overhead.

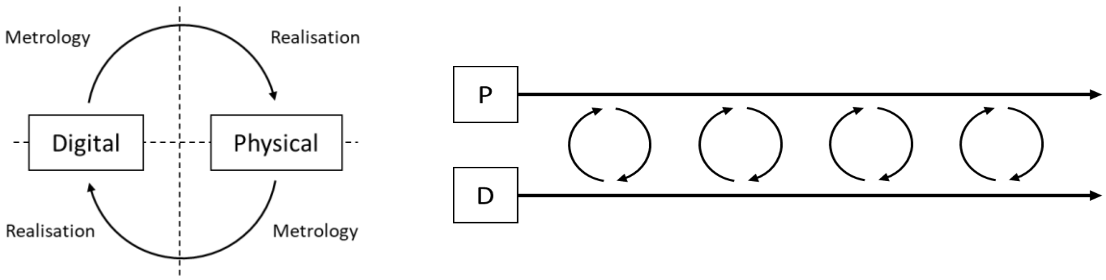

Figure 2. (L) Digital twinning cycle, adapted from (Jones *et al.*, 2020). (R) Digital twinning workflow

Digital twinning is represented as shown in Figure.2, comprising a physical entity, a digital entity, and the data connections between (Jones *et al.*, 2020). Twins are synchronised via a process of metrology (capturing parameters of interest from one entity) and realisation (updating the other to reflect the state of the first), with a theoretical goal of real-time synchronisation and complete transfer of all possible parameters between the entities across domains. Over time this process implies a workflow as shown in Figure.2 (right), where both physical and digital entities are maintained and updated bi-directionally.

For twinning workflow to be viable both digital and physical entities must then exist, be persistent, and be fair reflections of each other such that parameters may be meaningfully updated. This is not the case during the prototyping process - while entities are present across physical and digital domains they are not persistent over time, are evolving and in-flux, and a counterpart in the other domain that can be viably synchronised does not always exist. This challenge may be one reason why twinning approaches are to-date mainly applied to operational phases of the product lifecycle and are yet to penetrate to earlier design process stages, as observed by Jones (2020).

However, while not directly and fully transferable, the principal tenets of DTs may still be applicable in prototyping to create value. Rather than create persistent 'twins', DT principles raise the question of how domains may be best integrated to streamline processes, support learning, and realise and maximise the strengths that each domain provides. This sets two challenges for integrated physical-digital workflow

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in prototyping, **[1]** to enable sustained data connections between entities across domains, and **[2]** to support rapid cross-domain learning/action loops to improve the process or product. This concept has been shown in principle to have clear emergent benefits (Kent *et al.*, 2019; Kent *et al.*, 2021), such as tangible interaction (via physical) supported by real-time by digital analyses, and rapid reconfiguration (via digital) of physical prototypes allowing quick exploration cycles. Questions remain, however, to how these challenges may be met, the degrees of integration that are viable, and the benefits that they enable given the characteristics of prototyping processes.

2.3. Enabling technology for cross-domain integration

Effective physical-digital integration for prototyping requires the means to capture, interact with, and re-represent entities across domains rapidly and flexibly. Such a capability could allow each domain to be leveraged according to its strengths in accelerated learning-loops, supporting decision-making.
To this end, recent advances in the fast-maturing field of Immersive Technologies (abbreviated to XR) provide a means. Encompassing such technologies as Mixed Reality (MR, inc. Augmented and Virtual reality - AR and VR), haptic feedback, and gesture control, XR technology seamless links the physical and digital domains such that digital entities may be interacted with physically, and physical entities may be augmented with digital forms or information. Coupled with rapid digitisation technologies XR then provides opportunity for seamless, real-time, bi-directional synchronisation and interaction between physical and digital. In so doing they may enable the extracted tenets of DTs - learning/action loops between physical and digital, enabled by persistent data connections between the domains.
XR itself can be traced back decades (see Sutherland (1968)), but underlying technologies have only recently matured to become viable for wide-spread adoption. They are now poised to reach ubiquity in the workplace (Deloitte, 2021; XR Association, 2020) and create a step-change in how engineers interact with products, with many emerging examples of application within recent years (Kent, Snider, Gopsill, *et al.*, 2021). Recent work directly within the design domain has shown the potential and emergent value of these technologies for design development, including for MR (Kent, Snider, Gopsill, *et al.*, 2021) and gesture control (Gio *et al.*, 2021; Harlan *et al.*, 2021). Immersive technologies then provide a lens and opportunity to explore how physical and digital models may be integrated for design prototyping, the integrated workflow opportunities that may be created, and if and how emergent benefits of working across domains may be realised.

3. Integrated Physical-Digital Workflow for Design Prototyping

Current prototyping practice utilises an orchestration of physical and digital models that are created and synchronised freely by the engineer, often on an ad-hoc basis (Goudswaard, Gopsill, *et al.*, 2021), see Figure.3. As prototypes are often fabricated with a specific purpose in mind, they are also often single-use and inflexible, and are bound by the inherent weakness (and strengths) of the domain in which they were created. Transitioning between prototypes and domains is necessary at regular intervals, with learnings from one prototype captured and integrated into the next for subsequent testing (i.e., scanning of a physical prototype to update CAD geometry). Accordingly, the divide between physical and digital in prototyping, in addition to enabling the weaknesses of each domain, introduces a non-zero transition cost between physical and digital entities.

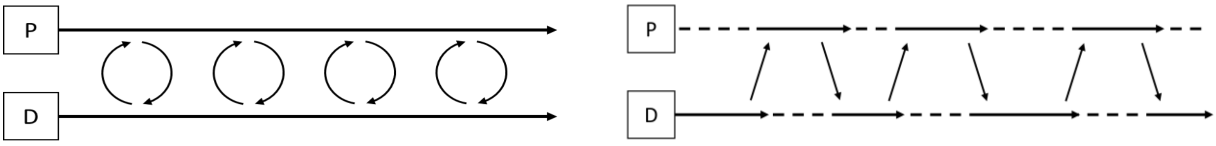

Figure 3. (L) Digital twinning workflow. (R) Typical prototyping workflow.

Taking inspiration from Digital Twinning, this paper explores integrated physical-digital workflow opportunities afforded by recently emerging XR technologies. By analysing four case-study implementations it investigates value, how integration may be realised, and implementation challenges. Cases are classified against a framing derived from engineer-prototype interaction activity and digital-physical synchronisation.

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3.1. Dimensions of cross-domain integration

To understand how integrated workflow might manifest in prototyping, it is necessary to understand how the challenges set by DTs (see Section 2.2) may be met and described in integrated prototyping workflow. Challenge [1] set a need for persistent data connections between physical and digital entities. In DTs, cross-domain data connections synchronise a subset of parameters across physical and digital entities, creating some level of co-dependence between them where the state of one will evoke change in the other. For example, a highly integrated digital twin may capture many parameters, run diagnostic and prognostic simulation, and automatically introduce an intervention back into the physical to improve performance. This work takes these two spectra - the degree of intersection in parameters that are synchronised between entities, and the degree of dependence between linked entities across domains, defined in Table 1. Challenge [2] set an additional need for physical-digital integration to support learning/action loops. As the purpose of prototyping is to support engineer learning through their interactions with the prototype (Camburn *et al.*, 2017; Houde and Hill, 1997), the user must also be considered to play a vital role in the learning/action-loops of prototyping. User-prototype interactions are bi-directional; the user may manipulate the prototype during prototyping (user → prototype), and the prototype also transmits information about itself to the user, for example via interpretation of its performance (prototype → user). Where currently these interactions occur either in the physical domain or the digital depending on the prototype, integrated workflow proposes spectra where these prototype ←→ user interactions could occur simultaneously across linked physical and digital entities. For example, separate physical and digital models with data connections between, through to fully integrated physical-digital interactions using a combination of MR and haptic interfaces.

These four classifying dimensions are illustrated in Figure.5 and defined in Table 1. From these dimensions it is possible to appraise prototyping workflow by degree of physical-digital integration, and elucidate the value of such workflows and the DT paradigm as applied to earlier design stages.

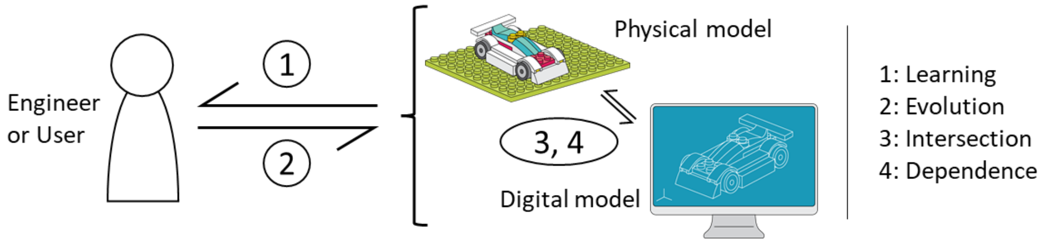

Figure 4. Physical-digital and user-prototype integration dimensions

Table 1. Integration dimension definitions

	Type	Dimension	Definition
1	Prototype-User	Learning (scope of)	The degree to which the user experiences or learns from entities in each domain separately or simultaneously.
2	User-Prototype	Evolution (scope of)	The degree to which the user manipulates and evolves entities in each domain separately or simultaneously.
3	Physical-Digital	Intersection (level of)	The degree to which all parameters of entities in each domain are synchronised.
4	Physical-Digital	Dependence (level of)	The degree to which the entities in each domain are dependent on each other for their state.

4. Case Studies: Integrated Prototyping Implementations

To appraise examples of integrated workflows in prototyping four case study implementations were developed and reviewed with respect to the four dimensions. In addition, current practice was also reviewed. The workflows are intended to be representative of approaches that may be leveraged as technologies develop, highlighting opportunity and challenges of integrated prototyping. This is used to investigate and contrast degrees of integration (via the dimensions of Table 1) and to elucidate the benefits that these integrations may create.

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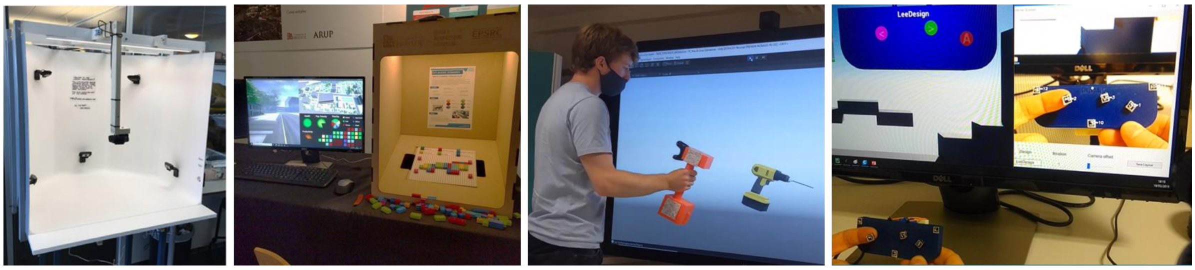

Figure 5. Integrated Workflow cases (left to right) Protobooth[1], CityBlocks[2], Digital Mirror[3], Augmented controller[4]

Case 1 - Current Practice:

Evolution	Each domain separately	Intersection	None
Learning	Each domain separately	Dependence	None

Current prototyping practice comprises an orchestration of physical and digital models designed and tested as-needed on an individual basis. Digital and physical versions of prototypes are created as engineers transition between domains but data connections are rarely, if ever, maintained with the exception of CAD/CAM and scan-to-CAD tools, and prototypes will not generally be co-dependent upon one other excepting manual update should an engineer deem it necessary.

Case 2: ProtoBooth - 'Twinned' Physical to Digital workflow

Evolution	Primarily physical domain editing. Domains are edited separately.	Intersection	P → D: Information, visuals, some geometry. D → P: None
Learning	Each domain separately	Dependence	Low. Digital is a partial instance of the physical.

Protobooth (Erichsen et al., 2021) is a digitisation platform for capture of parameters of a physical prototype and comprises scanning hardware, user interface, and a back-end knowledge database. This enables physical prototype version control, which may also be aligned to digital version control systems. Prototypes are digitised via cameras, with user-entered information on prototype usage, testing, rationale, and design precedents. Dependence and intersection of physical and digital domains is low with domains remaining separate. Value is realised through decreased physical to digital transition time and support of decision-making through the generated body of knowledge. Activity of the engineer is not substantially altered; rather the 'digitally twinned' versions provide a knowledge base to support decision making and process control.

Case 3: CityBlocks - Lego and Virtual Reality City Design Platform

Evolution	Primarily physical domain editing, with digital updated to reflect.	Intersection	P → D: Information and position of bricks synchronised automatically. D → P: None
Learning	Primarily digital domain via VR. Domains are experienced separately.	Dependence	State of digital depends completely on physical.

CityBlocks (Kent *et al.*, 2019b) comprises both physical and digital prototyping entities with automatic physical to digital synchronisation. Using Lego® bricks, users design a city comprising a number of building types (i.e. residential, commercial, school) on an 8x8 brick grid, which may be scanned via webcam at any point. Scanning detects building type and position, then generating a full-scale high fidelity virtual model that may be explored in virtual reality. Automated analyses of the city reveal the city's performance, supporting iteration and improvement via the physical entity. Integration is increased from Case 2 as the digital prototype is entirely dependent on the physical, creating a cross-domain prototype. While the physical to digital synchronisation is automated there is no digital editing capability and any design iteration must be performed manually. A key benefit lies in the analytics, which are enabled by higher dependence and intersection; high-fidelity capture of configuration enables high precision analyses to be run and fed back to

[1] (Erichsen *et al.*, 2021) and https://dmf-lab.co.uk/prototwinning/pro2booth-capturing-the-physical/
[2] https://dmf-lab.co.uk/blog/cityblocks/
[3] https://dmf-lab.co.uk/immersive-prototyping/
[4] https://dmf-lab.co.uk/blog/augmented-prototyping-reconfigurable-functional-interfaces-for-real-time-user-customisation/

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the user. Cross-domain user interactions are also beneficial - the physical entity as editing interface increases tangibility and accessibility, while the synchronised virtual prototype provides experience of the design at realistic and understandable scale.

Case 4: Digital Mirror - User-led configuration design and ergonomics

Evolution	Editing of prototypes can occur in either domain, but is separate in terms of what is/can be edited.	Intersection	P → D: Configuration and position synchronised automatically. D → P: Indirect, via AR overlay
Learning	Both domains experienced by the user simultaneously.	Dependence	State of digital depends completely on physical.

Comprises physical and digital entities that are directly linked in 3D space via lightweight positional tracking. A low-fidelity, modular physical prototype of a drill is assembled by the user according to their preference. This physical entity is tracked and rendered as a digital counterpart that appears on a screen in front of the user, presenting the prototype as if reflected in a mirror. The digital version is rendered at substantially higher fidelity than the physical and can be aesthetically altered in real-time. The user is able to see themselves in the 'reflection' holding an as-designed representation of the product overlaid on the physical prototype, thereby experiencing both domains simultaneously. Higher integration allow editing in either domain and simultaneous experience of both, letting users leverage each to generate wider learnings in a shorter timespan. Dependence of the digital on the physical ties learning to the tangible object in the users' hand, with positional intersection enabling cross-domain learning and scope for overlay of real-time analyses. Interaction itself is largley physical, but leverages modularity and flexibility to support design exploration, while digital renders maintain high fidelity.

Case 5: Augmented Controller - Integrated physical-digital prototype for user-led design

Evolution	Primarily physical domain editing, with digital updated to reflect.	Intersection	P → D: Configuration, position, and behaviour synchronised. D → P: Indirect, via AR overlay
Learning	Both domains experienced by the user simultaneously.	Dependence	Prototype is co-dependent on elements in each domain working simultaneously.

Integrated physical-digital prototyping system comprising a low-fidelity physical model with a reconfigurable electronic interface. The interface is directly tracked for both position and user interaction, digitising both positional and behavioural performance. Buttons may be reconfigured while maintaining 'function' via simulations driven by button presses. Digital entity comprises an AR representation of the prototype on-screen or overlaid onto the physical, and may be augmented with further analyses including internal packaging. The prototype requires both domains to function, with each playing a critical role in the learning process. The increased co-dependence drives capabilities beyond those possible when isolated to a single domain - the physical increases tangibility, while simultaneously the digital emulates behaviour. This increases accessibility and level of understanding beyond that of Case 4, where editing of the physical and digital remained separate.

5. Discussion

Comparison of Cases: Each case has been appraised against the dimensions of integration and can thus be visualised with respect to each as spectra (relative continuums), see Figure.6. Note that position on each dimension is indicative and relative to others on that same spectra only, without quantitative precision. Each dimension is then discussed in context of each case and the capability and value generated in it.

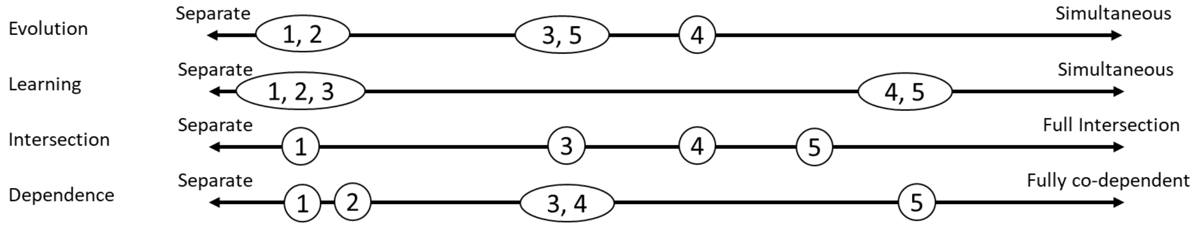

Figure 6. Comparison of the cases against integration dimensions

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Evolution: Cases 1 and 2 require each domain to be edited separately. Cases 3 and 5 use the physical domain as an interface, with changes also updated in the digital. This process both removes the need to transition between domains (reducing time taken) and also enables additional capabilities such as behavioural simulation to provide additional learning. Case 4 allows editing in either domain with higher integration; physical edits are immediately reflected in the digital, and digital edits are overlaid into the hand of the user. Within this set of cases, greater evolution 'twinning' enables broader learning with reduced transition cost and higher process efficiency.

Learning: Cases 1, 2, and 3 require the user to experience each domain in isolation. For cases 1 and 2, users interact with physical and digital for different purposes, but for 3 the purpose aligns with that of the physical - exploration of form and behaviour. Cases 4 and 5 allow experience of both physical and digital versions of the prototype simultaneously and use this capability to enable accelerated additional understanding, in each case overlaying digital analysis or behavioural emulation directly onto the physical prototype to support tangible decision making. Within these cases, higher *learning* integration increases the tangibility of interaction with the prototype, speeding up the process of learning.

Intersection: All four cases can be considered to embody increasing degrees of intersection. Case 2 introduces basic synchronisation to support record keeping and provide decision-making information. Case 3 introduces real-time synchronisation of form to allow fully rendered VR experiences of the prototype, enhance user experience, and enable digital analyses. Case 4 increases synchronicity via transitions back from digital to physical via AR, enabling user experience across both domains simultaneously. Case 5 introduces behavioural synchronisation in addition to form and position, enabling functional simulation and higher levels of interactivity. Within this set of cases, higher intersection increases the degree to which the strengths of each domain may be leveraged for benefit, enabling capabilities that increase speed of learning and interactivity for the user.

Dependence: In case 1, physical and digital are fully independent. In case 2 the state of the digital is influenced partially by the physical, streamlining the digitisation process and allowing knowledge capture. Cases 3 and 4 extend dependence by in-part making the physical an interface for the digital model, with physical changes then enabling accessible exploration of digital analyses and augmentation of the physical form via digital rendering to support better understanding. Case 5 greatly increases dependence to enable new capabilities, allowing interactive and tangible reconfiguration with a maintained function that would otherwise not be possible to create. Within this set of cases, higher physical-digital dependence is an enabler for interactivity within the integrated prototype and for novel capabilities in which digital analyses directly supplement physical exploration and learning.

Feasibility of integrated prototyping workflow: This relatively narrow set of cases evidences the feasibility of integration and that the challenges set by DTs may be achieved to varying degrees, with accompanying variance in capabilities and modes of working for the user. It is notable that Case 2 - which is closest to Digital Twinning as currently applied in industry - has relatively low integration by each of the dimensions and, while providing apparent value, does so in a form that is limited to information transfer and cannot fully take advantage of the affordances provided by each domain.

Value of integrated prototyping workflows: Comparison of the cases shows substantial variance with different technological approaches to increasing integration. This is important when considering technical implementation for new integrated prototypes - not only are there many options, but good practice that maximises benefit is likely not presently known. In the general case, benefits seen include accelerated processes, broader learning at an accelerated rate, reduced transition time between prototype versions, increased tangibility and interactivity, and deeper learning (i.e., via simulations or as-designed renders) at an earlier design stage. While early indications may be drawn of the specific benefits of integration over the four dimensions, such as more integrated learning correlating to accelerated understanding and of the prototype, further study is required to clarify value propositions.

Comparing to the strengths of physical and digital prototypes (Figure.1), the cases show that integrated prototypes may increase tangibility of prototyping for the digital version, by using the physical as an accessible and interactive interface (cases 3, 4, 5). Another strength lies in flexibility, where digitisation of the physical enabled a range of analyses from performance modelling to full-scale interactive renders. This digitisation process also supports replicability of the physical prototypes, where position, forms, and behaviour may be digitally stored for (e.g.) recall, lessons learned, and sharing across product teams.

Integrated workflow in prototyping activity: These cases demonstrate value across prototyping purposes (see Figure.1) and activities. Cases 3, 4, and 5 show enhancement of learning against *look and feel* via their tangible interfaces and as-final renders, while also allowing better understanding of *role* (via analysis / simulation of system performance) and *implementation* (via reconfigurable interfaces and associated mechanical analysis, case 5). In particular, cases 4 and 5 show potential for integrated prototyping to allow streamlined testing across multiple purposes at much earlier process stages.

Implementation challenges and technical debt: While this work has not explicitly considered the technical challenges of implementation, it is important to note that the implementation time/cost of each case and XR in general is substantial (days/£thousands). With increasing levels of integration the design and fabrication of the prototype itself increases in effort (Kent, et al. 2021), and a question currently remains of whether the benefits of integration outweigh the cost. While some cases were designed to generate value in a range of activities, these were also higher in cost and time to create than integrated prototypes designed for specific activities. There is a strong case for future research to consider minimum-effort integrated prototyping workflows and associated best practice until cost of implementation decreases, such that technical cost is minimised and benefit is maximised.

6. Future Outlook and Conclusions

Derived initially from the principles of Digital Twinning, a rapidly growing and highly beneficial paradigm in engineering industry, this paper has considered and proposed integrated physical-digital workflow for design prototyping. Via four case study implementations it has explored how immersive technologies may be leveraged to realise the challenges set in applying DT tenets to prototyping stages, and the potential value that an integrated workflow may generate. It remains however a narrow study of technical implementations with opportunities for much future work:

- While indications of value have been drawn from different integrated workflows, little specific knowledge exists of how it may be maximised. Focused research is required to identify best practice, how such workflows may be implemented, and when in the process their value may be best realised. It is important to map the relative success of differing integrated workflows against prototyping process 'success', such that the relative benefits of different implementation options may be understood.
- The cases show varying degrees of integration, but are unlikely to be representative of every way in which integration may be realised. Further work should consider both 'common' forms of integration that are targeted towards specific value propositions, and also the effect of maximal integration in any or all of the dimensions - i.e., the maximum degree of integration that is both viable, and remains beneficial beyond the associated cost. With large technical debt associated with implementation, such mapping would support better method selection and ensure good outputs.
- Technical implementation may occur in a variety of ways, with a range of accompanying complexities, costs, and capabilities. How to best realise integration in any of the dimensions is not known, or even if/how each transition (see Figure.5) may be supported. For example, the physical-to-digital transition has been shown through a range of existing sensing methods, but the reverse from digital-to-physical has not, with no clear automatic and real-time method to physically update a prototype form. Further work should map the different elements of integrated workflow against how they may be achieved.
- Prototyping itself is a broad activity with highly variant goals. The intersection between integrated workflows and best practice given the specific purpose of a prototyping activity is currently unknown, including the potential opportunities of tailoring implementation towards specific process goals.
- Application of immersive technologies is an emerging field, but the development of the technologies has been a focus in other fields for many years. There are many relevant cases of implementation that may be drawn from, and broader evaluation is needed to understand how, when, and where they may inform effective use of integrated workflows in design (i.e. see Kent et al. (2021)).
- All work with XR must consider the technical costs associated with implementation. In tandem with best practice, further work must consider implementation and control of design effort such that the benefits of integrated workflow for the NPD process remain higher than the costs.

Through this exploration, this work has shown feasibility and potential for substantial value to be realised from more integrated workflow in design prototyping, including accelerated prototyping processes, increased understanding, increased flexibility, and increased tangibility and accessibility of the prototyping process.

However, there remains much future work before such integrated workflows may be realised in common practice to ensure effectiveness, streamline towards specific value propositions, and reduce implementation complexity and cost.

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