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USER ENGAGEMENT IN PHYSICAL-DIGITAL INTERACTION DESIGN

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ABSTRACT
This paper describes the development of a physical-digital demonstrator that makes use of augmented reality (AR) technology, to convey complex systems and engineering information for design education. As well as acting as an educational and client-facing tool for the industrial partner, the configuration and principles of the demonstrator point towards how physical-digital installations can be used in design education settings more generally. We will outline the development of case study material for human-centred design and product modelling and visualisation education. Initially we describe the nature of the bespoke tool, its features and user interaction. This segues into a discussion about how information is conveyed to the user through a series of engagement phases that are developed into a three-stage "Order of Engagement" framework. The real-world application of physical-digital interaction means the lessons learnt from the AR demonstrator design and Order of Engagement framework evaluation have clear practical and commercial applications for future digital interaction design.

Keywords: Interaction design, augmented reality, physical-digital interfaces, new educational tools

1 INTRODUCTION
In this paper, we explore the application of a physical prototype used in conjunction with an AR app. AR blends the real, physical world with digital, computed-generated elements, adding contextual layers of information to the users' sensory experiences of their physical environment [1]. Its ability to integrate additional information, instructions and explanation while retaining real-world interaction has enabled it to find broad applications in training and education [2]. The case we focus on in this paper relates to a specific technological use case, the dynamics of which could be applied within other contexts and settings. The physical prototype 'demonstrator' explored in the work is designed to be a tool in which a specific set of environmental conditions can be simulated and then augmented utilizing an AR app. The context of use can vary, but the core reason the demonstrator was developed was as an engagement and communication device i.e. allowing stakeholders to comprehend technological concepts and engage with interactions within particular constraints.
Firstly, we set out the case for physical-interaction and the Orders of Engagement framework that describes how physical-digital interaction experiences can effectively capture and retain user attention. We then describe its application in our specific case study, where the demonstrator prototype is used to convey the functionality of a complex engineering installation. Finally, we consider the implications of this by reflecting how design education and aspects of stakeholder engagement and buy-in can be positively impacted by bespoke prototypes of this nature.

2 WHY PHYSICAL-DIGITAL INTERACTION?
2.1 Engagement through information, narrative and context
Modern product experiences (particularly software dependent devices) is dependent upon a carefully configured bi-directional physical-digital exchange between the user and the artefact [3]. Since the emergence of digital interface and particularly smartphones, there has been an emphasis within a product development context of creating seamless digital "narratives" in which users can freely navigate a device without much prior knowledge of its functions [4]. Using design features such as physical vibration or skeuomorphism [5], modern digital devices aim to use an architecture of intuitively understood emotional markers and culturally distinct symbolic signifiers to generate a seamless use experience [6]. Users are now expectant of a coherent, compelling experience that means the digital information flow should be appropriate, timely, and sensitive to context. Concepts such as the diegetic interface can be

helpful in creating an integrated physical-digital experience, and in creating a strong narrative to the interface design [7].

AR represents a distinct case as the user is still interacting with the physical environment. However, it remains critical that the AR overlays are designed in such a way that they do not impinge on or detract from the natural interactions. What is crucial for AR is achieving a form of immersion despite the presence of an outside real world [8]. While older understandings of immersion and engagement proposed and single and unidirectional framing [9], more recent work has brought the context of individual personality and wider society into the frame [10]. Subsequently we can say engagement is a distinct subjective positioning of the user within the matrix of inputs delivered by the system resulting in experiences of flow, presence and immersion that are significantly influenced by the users' idiosyncrasies and societal influences.

2.2 Perspectives from human-centred design

Giacomin [11] has described how the apex of HCD thinking is meaning stating that "human centred design leads to products, systems and services which are physically, perceptually, cognitively and emotionally intuitive" (p.610). This approach has been fundamental to the development of digital computing tools and novel tools integrating the physical and digital realms. Early exploration of this such as the 'Triangles' project from MIT's Media Lab [12] took simple physical artifacts that could be electronically connected and created digital 'events' from their interactions. Similarly, the ATILIER project explored the use of digital augmentation in an architectural design context such as the application of virtual paint textures onto physical models [13]. The conceptual shift has even been explored in a digitally augmented version of the game Go [14] and within a museum context – itself now a commonplace feature within interactive educational environments [15]. Figure 1 shows the relationships between physical engagement and its cognitive and emotional value to users. In essence there is a constant state of flow between the cognitive and emotional that is mediated by the physical engagement.

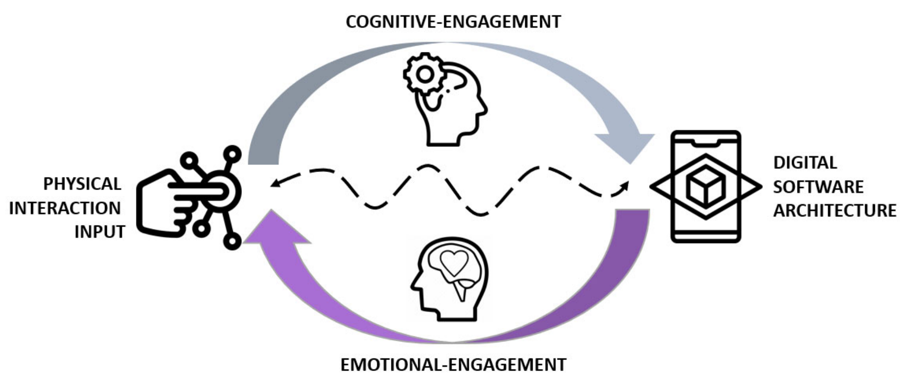

Figure 1. Figure showing key characteristics of physical-digital interaction

In relation to design several interesting projects track closely with the demonstrator we are presenting. Mazalek et al for example developed "Architales", a physical-digital co-design tool for interactive table for "tangible story telling" [16] and similarly Hartmann et al developed "Pictionarie", a tabletop device that allows design teams to transfer sketches, notes or images from the physical to the digital realm [17]. Following this vein, we have previously developed a VR-based prototype, the "Control Carousel", that allows design teams to review products in an interactive digital environment. The work identified several characteristics in relation to a successful engagement with a VR based prototype: accessible, reassuring, contextual, satisfying, collaborative [18]. This tracks closely with other work from the University of Bristol on physical-digital integration in relation to digital twins who concluded learning, evolution, intersection, dependence are the key factors for a successful engagement [19].

3 ORDERS OF ENGAGEMENT FRAMEWORK

To formalize the properties of user engagement with physical-digital interaction, we have generated an "Order of Engagement" framework that characterises the nature of interaction with physical-digital interfaces (Figure 2).

	Order 1	*Order 2*	*Order 3*
Physical	Configuration of basic model composition	Manipulation of representative elements and artefacts	Interaction with detailed data streams
Digital (information)	Abstraction of design context via extraction of visuals, dimensions	AR overlay representing functional elements of system	Live data and analysis of system performance
Product interaction example	Manual typewriter inputs	Inputting of text into a computer interface	Interaction with a gaming controller and game architecture/narrative

Figure 2. Orders of engagement in relation to physical and digital interaction

1. Observation of system architecture and location conveyed through static representation, which can also be mapped in physically prototyped, adjustable models.
2. Interaction with information and representations of system functionality through AR artefacts via the mixing of physical prototype models and digital interfaces. E.g. apprehension and manipulation of design features
3. Integration of dynamic conditions and performance captured in-situ, which will be communicated through live simulation. E.g. convergence of real-time and historical data

4 OVERVIEWS OF PHYSICAL-DIGITAL TOOL

Working in conjunction with Siskin Asset Management, a company that specialises in developing lo-tech solutions for coastal erosion problems, we developed a prototype tool that allowed for the simulated visualisation of this technology. The prototype tool utilises the Order of Engagement framework (Figure 4) in order to create a more compelling way for Siskin to communicate with clients and external stakeholders when explaining the function and installation of their system. It consists of several features that allows the user/s to build a representation of the target coastal site and then to digitally visualise, utilising augmented reality, how the Siskin technology would appear within the environment.

The representation of the target environment is created by adjusting a set of levers, the position of which broadly conform to the sea, beach and sand-dune that make up the real environment. By moving the relative position of the levers along the rails and using the wheel-cranks to adjust the high of the surface, a range of landscapes can be created. As the surface was prototyped using a magnetic sheet, custom AR markers could be deployed and placed at any point on the sheet without sliding off.

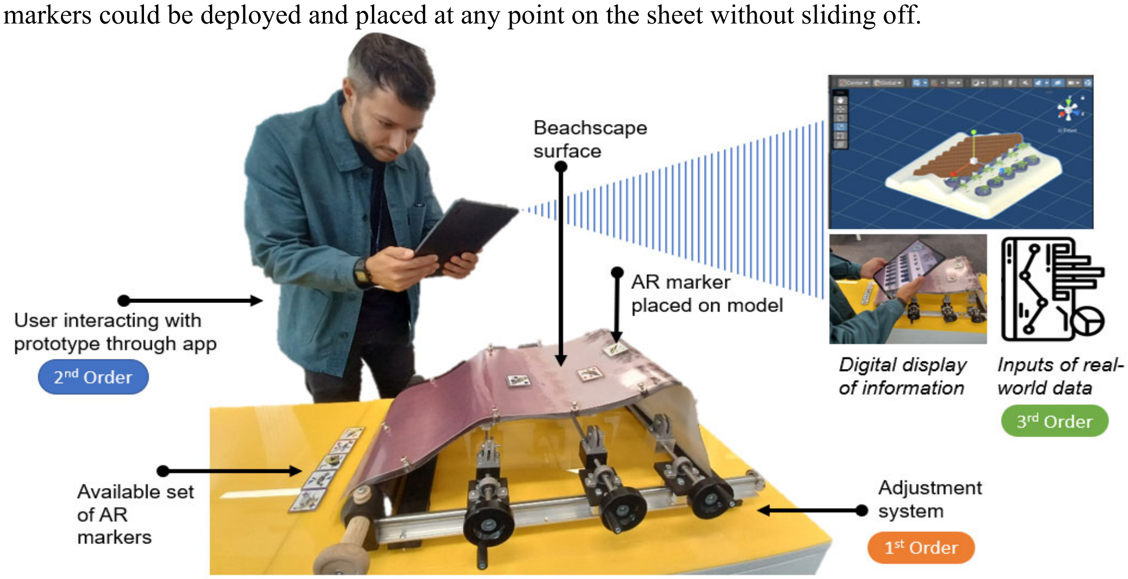

Figure 3. Elements of the physical-digital visualisation tool

A diagram of the tool's key features in relation to the Order of Engagement framework is shown in Figure 3. The first order is defined by observation and building a static representation of the target site. In essence, this is a process of abstracting the real world. The second order is defined by initial interactions with the AR representations that provide an insight into how the Siskin technology might look within the real world (albeit as abstracted version). The third order is defined by the integration of more intelligence into the AR digital interface that allows the user dynamic control over the visuals such as installation detailing or time-lapse sequences showing the growth of sand dunes, vegetation and bio-diversity markers.

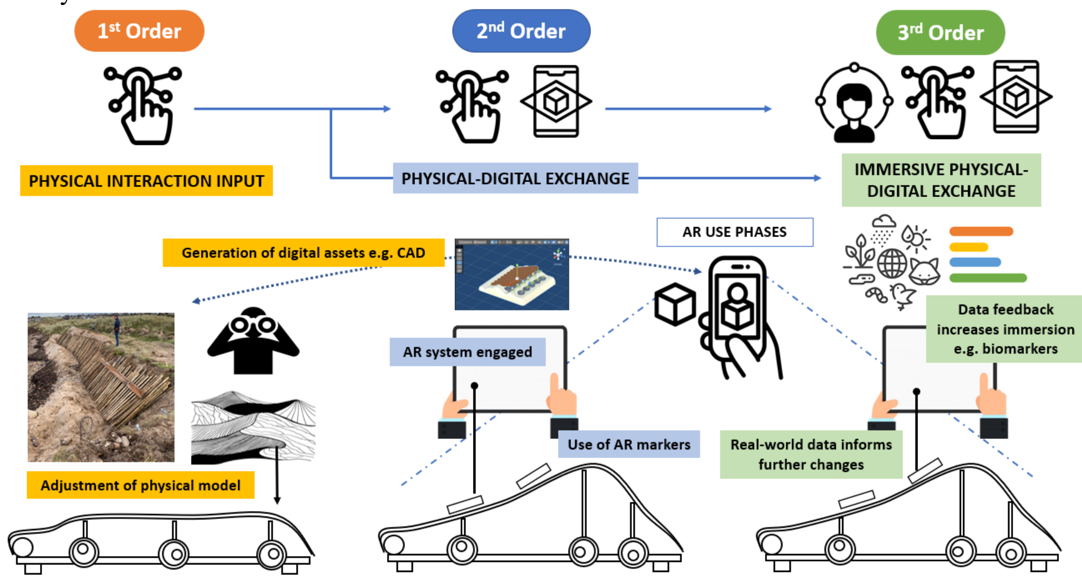

Figure 4. Orders of Engagement model for interacting with the prototype

The tool is designed so that the user can freely move around it i.e. it does not need to be attached to a wall and does not require electrical input. Ideally it is placed centrally on a small table and the user(s) can move around its perimeter and interact with it both physically by adjusting the landscape parameters or digitally by using the simple AR app and freely changing the positions of the AR markers of which we created 8 unique variations, each loaded with a different visualisation model similar to that shown in Figure 3.

Linking back to some of the earliest examples of physical-digital tools such as MIT's Triangles, the demonstrator moves between the physical and the digital as the user moves through the phases of use. There is an initial manipulation of the model – the relevance of the digital here is negligible as the user negotiates the physicality of the device. Then there is the introduction of AR which brings two narratives together, one abstract but real, the other conceptual or hypothetical. This is similar to a process of world-building in the user's mind [20]. This AR dimension can then be directly manipulated in various ways – almost like an opposing force, the physical reasserts itself as the user can reconfigure the parameters of the AR presentation. This "negotiation" between the physical, digital and the interaction between them links with the model presented earlier (Figure 1) whereby the engagement is the "engine" behind cognitive and emotional payoff for the user.

5 APPLICATIONS TO DESIGN EDUCATION

5.1 Technological acceptance and user satisfaction

We can now explore a number of scenarios that relate to design education. Since the relation between users' physical engagement and cognitive value was previously discussed in Section 2, the first explored scenario concerns the adoption of the developed framework in modules following Human-Centred Design approaches. In particular, the engagement orders can contribute to the planning of user-led design investigations and tackle issues related to technology acceptance and user satisfaction. Providing that the application of VR/AR in HCD projects has been quite prevalent over the last years, in the existing scenario students could focus on the design of the tangible element of the product that is integrated into VR/AR environments and enhance the overall user experience. Consequently, design assignments of such nature predominantly address the first two engagement orders through 1) observation of user experiences through HCD methods and 2) merging of physical-digital worlds based on identified context and user requirements and should aim to promote the delivery of "physically, perceptually, cognitively and emotionally intuitive" solutions for distinct problems.

5.2 Learning and technical familiarity

The second educational scenario concerns students' learning and familiarity with such emerging technologies and aims to advance the way in which they perceive digital interactions during CAD and 3D modelling related courses. Insights from previous case studies [21] have already been implemented to introduce students to the benefits of VR applications in design reviews, and model exploration in immersive environments. Outcomes from the aforementioned case study can be framed to structure the lecture contents of a digital visualisation class and show how the three engagement orders can exploit the benefits of such interactions. In detail, Orders 1 and 2 can be used to develop technology-related challenges and prompt students to reimagine AR controllers beyond digital interfaces and explore how different types of physical props can be used for manipulation and refinement of digital models or navigation of virtual environments, through multiple modes of haptic feedback. Following that, Order 3 should focus more on adding new knowledge dimensions via studying the ways in which real-time data can be transferred and visualised through the convergence between AR and Digital Twin technologies.

5.3 Prototyping roles through the framework

Lastly, the third scenario belongs to the theme of prototyping and addresses the ways in which distinct prototyping roles can be served through the application of our framework in academic design projects. In detail, the three "Orders of Engagement" can have a valuable impact in students' decision making when it comes to selecting suitable formats for their prototype models [22] for demonstration, communication and design refinement purposes. Students' prototyping tasks can be alleviated through the process of augmenting physical models with useful digital information, to efficiently communicate their properties and function to project stakeholders, e.g. end users during testing and educators during critique assessments. Exemplars may include the overlaying of a quick mock-up model with rendered appearances to present aesthetics, integrated animations to demonstrate function and employment of Digital Twin to visualise potential impact and performance of concepts. On the other hand, the same mechanisms can also be applied to iteratively refine and evolve their ideas through testing in later design stages, as AR-based simulations can support optimisation of a concept's performance by acquiring real-time experimental data through Digital Twins. Thus, the three engagement orders could also contribute to the evaluation and validation of technical specifications and requirements, while ensuring the whole system's functionality and compatibility of its parts.

6 CONCLUSIONS

This paper has outlined a conceptual model in which physical-digital interaction can be understood within an "Orders of Engagement" framework. By firstly exploring the key theory of interaction and highlighting a number of prominent research example we developed a three-fold engagement framework that emphasizes the exchanges between physical and digital interaction and the cognitive and emotional payoff a user can get from these interactions. We then introduce our demonstrator prototype, used to explore these concepts in more detail and showcase how augmented reality can be used in interesting ways in conjunction with a physical prototype arrangement.

Providing that emerging technologies such as Augmented Reality and Digital Twin are constantly developing, it is vital for design and engineering education to parallel with their changing nature and ensure that they are capably integrated into teaching practices and curricula. In STEM subjects particularly, AR can be employed to enhance spatial ability, conceptual understanding and visualisation skills by functioning as a blended learning and teaching tool [23]. Consequently, future study will investigate how its potential applications in engineering and product design educational settings can enrich the adoption of digital tools in design workflows through exploring the intersections between physical and digital technologies. The intersection of physical and digital continues to be a compelling area. This case study shows how these technologies are redefining our relationships with society and the environment and offer new possibilities within the space of design and engineering to create new tools of creativity and education.

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