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COMPUTATIONAL DESIGN, ADVANCED VISUALISATION, AND THE CHANGING NATURE OF CAD

ABSTRACT
Computational design and advanced visualization are two key avenues of development that are changing the landscape of CAD for engineering designers and much of the work in computational design has been pioneered and applied most enthusiastically in the field of architecture. Known informally as the 'computational turn' that started to make a significant impact around the early 2010s, the associated modelling methods can significantly affect the methodology for the construction of CAD geometry and the nature of forms that are achievable. When combined with VR and AR interfaces, these allow potential designs to be explored in 3D and in real time to further affect the design process. To this end, relevant literature and emerging trends will be set out. A case study will then be presented based on the PRIME-V2 research project, which is concerned with the delivery of bespoke VR controllers to allow users to perform physical rehabilitation. The main insights derived in terms of the design process, capturing user requirements, generation of bespoke data, prototyping and testing, and technical limitations will be highlighted. The implications for the delivery of CAD teaching for postgraduate engineering designers will then be considered. This will be via the experience in redesigning a module at the University of Strathclyde. Titled 'Product Modelling and Visualisation', the module has sought to move beyond basic feature creation skills towards an understanding of where and how advanced computational techniques can be deployed in the design process at large.

Keywords: Computational design, visualisation, CAD, design process

INTRODUCTION

Teaching of CAD is an essential part of product design engineering courses. However, simply learning to use a basic parametric system for the construction of geometric models is no longer enough. Given the rapidly shifting nature of the CAD landscape, and in order to provide more strategic contributions, graduate design engineers should understand the rationale behind how models are constructed and have an awareness of how emerging techniques can be deployed within industrial settings.

This paper firstly sets out the history and context of CAD. It then describes two important aspects of development that are changing the landscape of CAD for design engineers: computational design and advanced visualization. Computational approaches to CAD differ from conventional practices in the level of dynamism and intelligence present in the construction of the geometry. Often constructed using visual programming paradigms and utilising interactive technologies such as VR and AR, it offers new possibilities in both modelling and interaction through the design process. In terms of design education, this has implications for the teaching of CAD and for the way in which facilities are presented to students. A number of illustrative examples are outlined via the PRIME-VR2 project on VR for rehabilitation. In the generation of novel control interfaces, this work has used computational approaches in order to create bespoke and optimized design configurations. The effect of an algorithmic approach on the design process, as well as instances of design detaining and model interaction, are described.

Secondly, the paper reflects on the pedagogy of CAD. How can we teach both the basic skills of CAD and convey its context, use and application in a single-semester class? We have approached this by providing a foundational exercise designed to be attainable for novice users, but with enough creative opportunities for more advanced users: cutlery. While at first glance this is a basic challenge, the details of tines, contours of surfaces, joining details etc. provide a range of challenges in achieving a truly convincing design, and a great deal of flexibility in the rendering thereof. The rationale for the configuration of the module is set out, and a number of recommendations on the future teaching and use of CAD in design engineering education provided.

CONTEXT OF CAD

History and emerging trends

CAD is a form of digitally displaying geometric information and principally emerged as a way to emulate the practices of the professional draughtsman. Principally, it took the system of lines and coordinates used to create representations in a physical drawing and translated that into computer code that could be visualised and interacted with directly using computer hardware [1].

While the very first systems allowed the creation of basic geometric shapes, the systems from the 1970s onward rapidly acquired more complexity and capability. The key breakthrough was the application of NURBS (non-uniform rational b-splines) into the CAD software architecture which allowed for the definition of free-form surfaces such as complex curves to be routinely modelled. This advance led to a rapid transition to feature-based model making and structuring CAD through a process of parameterization. This meant that the models could be built using a "tree" of interrelated features allowing designers to establish dimensional constrains and explore design space more freely.

As CAD modelling has become more complex, there has been more of a push towards menu-driven interaction with highly-developed user friendly interfaces, but it remains a demanding task to become fluent in a particular CAD package [2, 3].

In terms of the contemporary use and application of CAD, we identify two key developments: algorithmic modelling and advanced interaction (Figure 1). One is related to the logic and intelligence implicit in the construction of the design model. The other is oriented around crossing the physical-digital barrier and effective means of digital capture, communication and visualization allowing designers to explore design space more easily and fully. Each is addressed in more detail below.

Figure 1. Algorithmic modelling and interaction trends

Computational design is a new way of generating form. Much of the work in computational design has been pioneered and applied most enthusiastically in the field of architecture [see 4]. Known informally as the "computational turn" that has its foundations in the topological optimisation strategies developed from the 80s, it has made a significant impact in the last decade, with the associated modelling methods able to significantly affect the methodology for the construction of CAD geometry and the nature of forms that are achievable. Although terminology is somewhat fluid within this field, Stasiuk's [5] breakdown is useful; **parametric design** - creating geometry through a hierarchical, feature based model**, computational design** - creating geometry though a logic-based algorithm and **generative design** - creating multiple options through recursive development and intelligence within design system. "Generative design" is a narrower description but can be thought of as a subset of computational design where the solutions are more open-ended and will emerge from the solving process. Parametric design is in essence not a computational design method though it can be used with a range of optimization methods.

It is best to approach understanding computational models by making direct reference tools and perhaps the most widely used is the Rhino 3D plug-in Grasshopper. Grasshopper facilitates complete command over the parametric build of the 3D model, allowing the designer to directly control the geometric constraints and build the logic of the model in a precise way they desire. The command over the geometric data can then be combined with form finding algorithms (of which there are many available as applications within Grasshopper itself and freely downloadable).

When combined with VR and AR visualisations, computational methods allow potential designs to be explored in more dynamic ways such as direct use simulation or in-situ visualisations. Grasshopper itself presents an interesting way of constructing CAD where the designer can use a range of drag and drop functions, connection nodes and value sliders to edit and interact with the model. Taken into a VR context, this process becomes even more interesting whereby the designer can view and interact with the concepts in specific environments and settings. Conceptual work in VR interface design has demonstrated this potential in the context of design reviews for example [blank for review]. Furthermore, architects are increasingly using VR to properly visualise and experience the spaces they design, and the fashion world is experimenting with the use of AR all of which present opportunities for interface reimagining and pedagogical considerations [3].

Case study: customised VR controllers

A range of computational design approaches have been adopted in the PRIME-VR2 EU project (https://prime-vr2.eu/), mostly utilizing the Rhino-Grasshopper (https://www.grasshopper3d.com/). The project is concerned with the delivery of bespoke VR controllers to allow users to perform physical rehabilitation tailored around their specific therapy needs. Furthermore, it seeks to create an integrated environment that starts with the biomechanical scanning of a user, through the generation of bespoke CAD, to the parameterization of the virtual environment in which the user interacts. The overall structure of the PRIME-VR2 project embodies a wide variety of advanced design techniques and technologies and presents an ideal case study for considering the fundamental changes in design practice that are emerging in the 21st century and the related challenges they present for pedagogy. `

Design methods in PRIME-VR2

In order to explore how new methods in computational and algorithmic design are influencing practical design work, we can unpack the methods utilized within PRIME-VR2. PRIME-VR2 partially follows the path of traditional design methodologies; relying on research, iterative conceptulisation and feedback that informs subsequent developments. Though in other ways, the methods employed are much more novel and innovative. Critically, the project takes a novel approach to the generation of product form and the workflow in which CAD is generated. As the main aim of the project is to create bespoke designs tailored around the individual user, ergonomic and other biomechanical data has been crucial in structuring the design methodology. We can summarise the key stages as follows and elucidate them in turn; **1) definition of abstract spatial boundaries 2) integration of unique ergonomic data 3) algorithmic exploration of design space 4) final design decision and CAD refinement.**

This workflow, outlined in Figure 2, lends itself to the development of algorithmic design methodologies as it seeks to expand the domain by which design solutions are formed. By reformulating the process not necessarily as a linear process of finding solutions, but as a more dynamic process whereby the form-finding strategies are moved closer to the user and the spatial envelopes in which the design options explored are more focused within a bounded solution space informed directly by relevant user data, in this case ergonomics. Abstract design solutions can thus be created earlier in the process, facilitating greater comprehension of form possibilities and articulation between form and functional requirements.

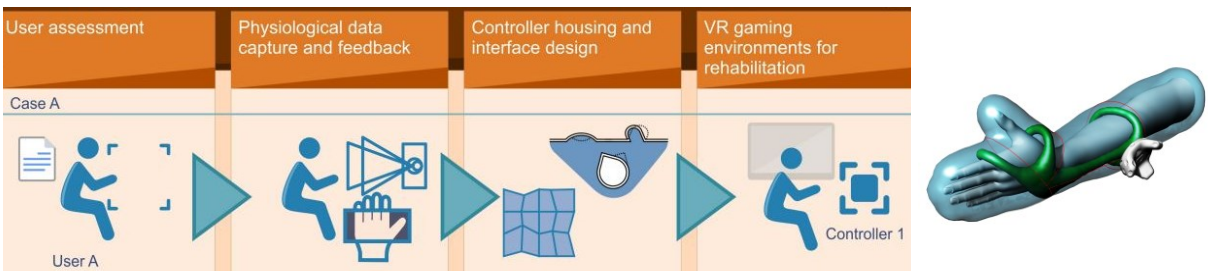

Figure 2. PRIME-VR2 workflow and abstract controller structure

In the case of PRIME-VR2 the unique anatomical profiles as derived from an ergonomic scanning procedure is combined with the abstract spatial boundary definition **(1/2).** This ergonomic data can then be utilised as the basis for algorithmic form finding **(3)**, with reference to the abstract representations that inform how the form finding processes are structured. The form finding processes will lead to a set of results that can be visualised in the CAD environment **(4)**, these can then be further refined by varying elements of the algorithm or separate editing procedures.

What this workflow highlights is how computational power can change and enhance the processes of design. Critically, PRIME-VR2 identifies creating abstract spatial classes as key to exploring design space and generating CAD. Focusing the computational efforts not on a very general problem but creating a more structured space in which the algorithm can explore and generate forms. The outlining of this workflow as explored within PRIME-VR2 sets the scene for a deeper analysis of how these approaches may be applied within the teaching of design and related tools such as CAD, sketch work or prototyping. The next sections will explore this in more detail by considering how these insights could be applied within the creation of a teaching module.

HOLISTIC TEACHING OF CAD

Challenges in CAD pedagogy

Teaching of CAD is an essential part of product design and engineering courses as students can easily create digital models to explore, imagine and test their ideas. While this is traditionally done with standard parametric modelling, the evolvement of technology has assisted in the development of modern CAD software which can be particularly useful for teaching and learning, as their integrated advanced simulation and visualisation tools can transfer the functionality of digital models to real-world scenarios [6]. Besides the aforementioned benefits of computational and generative design in previous sections, virtual reality is also regarded as a promising teaching tool that increases motivation and enjoyment of students while keeping them highly engaged [7], and can be valuable in cases of distributed projects and online collaboration. However, integrating VR into design modules comes with challenges mainly related to accessing necessary equipment and the associated costs for educational institutes [7]. Moreover, the software complexity and often intimidating user-interface of the total of these emerging technologies, in combination with limited time resources, impedes their comprehensive teaching in single-semester classes. Still, as dynamic course content and advanced digital visualisation tools of higher-level resolution and aesthetics, which are commonly preferred by students, tend to negatively affect creativity [8], a balance must be achieved between improving the quality of students' design outcomes while adhering to the principles of the design process.

Design education curricula have to keep up with the constantly changing nature of CAD technologies which evolve into immersive 3D experiences or touch and gestured-based interfaces and are now finding application in numerous industrial fields. Therefore, educators have to ensure that teaching materials are updated accordingly as the emerging representational technologies are key to the access and sharing of knowledge in design studio learning environments [9]. Due to the huge range of different CAD software available in the market, educators tend to teach quite generalized guidelines and processes, instead of delivering in-depth tutorials of specific tools. This is also one of the reasons that CAD education should provide students with diverse tasks, forcing them to develop the ability to identify and associate the most appropriate media for specific design activities and therefore, show rationale and achieve autonomous learning [10]. In other words, students should demonstrate that kind of strategic CAD knowledge, instead of simply knowing a specific software's functions and the process of using them [11]. Research has also shown that CAD curricula should always be depending on the role CAD will play in the student's future career [11]; therefore, design education should cover a significant range of CAD technologies and let the students choose the most interesting to them. This is also related to the effectiveness of student engagement, as their intrinsic motivation tends to be increased when feeling that the teaching material is beneficial for them personally and related to their background skillset [12]. All the above challenges are even more evident in the case of postgraduate level modules, involving students of varying engineering disciplines and diverse levels of CAD experience. In these cases, educators have to ensure that CAD fundamentals are taught to a complete degree, while those already acquiring that basic knowledge can progress by improving their competence through more advanced CAD methods.

Design of a CAD module

Here, the implications for the delivery of CAD teaching are considered through the experience in redesigning a module at the University of Strathclyde ('Product Modelling and Visualisation') that has sought to move beyond basic feature creation skills towards an understanding of where and how emerging techniques can be deployed in the design process, while at the same time providing a base level of competence in the operation of a CAD system. In order to support this, concepts from the literature and instances from the PRIME-VR2 project have informed a structure that allows for an initial modelling exercise to be used as a foundation, for a more theoretical and expansive exercise in assigning and blending advanced techniques in the development process.

As a postgraduate module, this class must accommodate students from varying backgrounds and competencies in CAD. In order to provide a subject matter that allowed for the basics of solid modelling to be grasped, while at the same time providing the opportunity for more advanced forms to be explored, students were set the challenge of designing a cutlery set (knife, fork, tablespoon and teaspoon). While this seems a straightforward task, on closer inspection it provides a good range of modelling challenges. It is something familiar that students can relate to. And there are items at hand for those who wish to build it around existing designs, but there is scope for innovation for those who are more adventurous. Also, time limitations certainly exist for students who have no significant experience CAD; however, this challenge encourages reflection, analysis, research and exploration. The assignment was split into two parts (Figure 3):

- Part A is the generation of a high quality visual, a technical visual and a technical drawing set. Full documentation and rational of the modelling process was to accompany these.
- Part B was the utilization of an advanced technique, chosen from a supplied list, and applied to one item of cutlery. Students were responsible for selecting their chosen technique and reflecting on how it could be implemented in a CAD workflow.

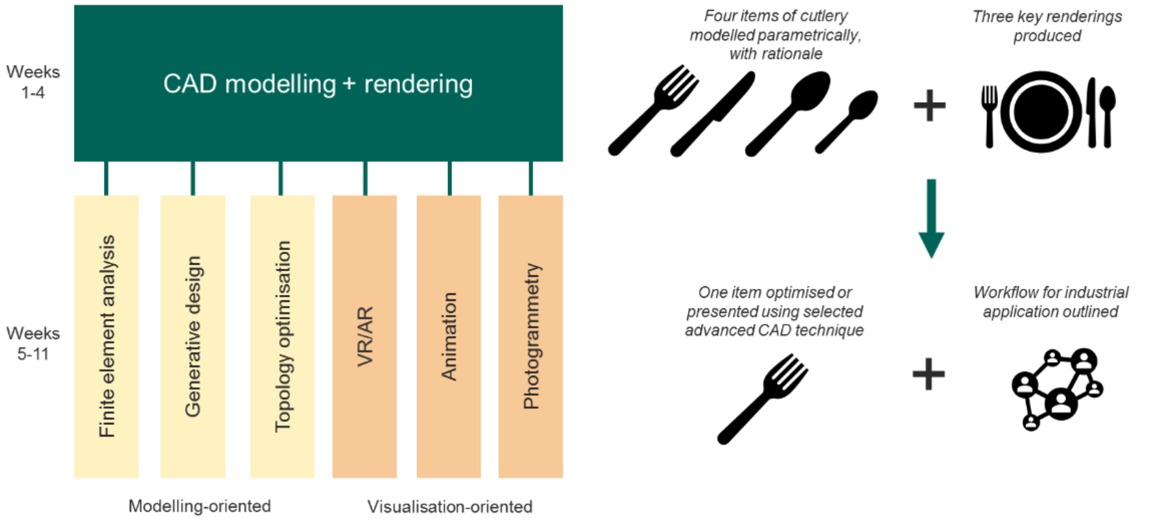

Figure 3. Structure of module (left) and expected output (right)

CONCLUSIONS

This paper discusses the context and history of CAD along with the two emerging techniques of computational design and advanced visualisation which are different to traditional modelling practices and have strongly contributed to its constantly changing landscape. For better understanding the effects of these emerging avenues, a case study on the PRIME-V2 research project is utilised to illustrate the novel methodology and CAD workflow applied in the design of bespoke VR controllers for physical rehabilitation.

Nevertheless, providing that the integration of advanced CAD teaching in design education raises a number of challenges, the paper also describes the configuration of a postgraduate module that seeks to provide not only foundational modelling skills, but scope to explore advanced CAD methods and reflect on routes to implementation. Literature findings and insights from the case study have contributed towards a novel structure of a two-part exercise which allows the graduate students to practice the basics of modelling while selecting and applying an advanced method which is suited to their design purposes, personal improvement and career ambitions. Therefore, CAD educators should ensure that technological progress is reflected in the content of teaching materials and besides of having to provide functional knowledge of emerging methods, they also need to demonstrate the accompanying challenges, appropriate application and reasonable selection of them to design students.

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