Conceptual Modeling in Product Design within Virtual Reality Environments

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Abstract. Digitalization has already permeated most of the design activities, but in spite of this, the generation of visual representations of concepts in the product design domain still relies on analog tools in real world contexts. Despite immersive 3D technologies, such as Virtual Reality, have become widely available and affordable, most designers still make use of pencils and paper sheets, or their digital counterparts, to sketch their initial ideas on 2D supports. This study aims at investigating the reasons behind the mismatch between the rapid growth of immersive technologies and their scarce adoption in the conceptual design activities. Based on the analysis of the state of the art, a classification of the approaches proposing new ways to conduct conceptual representation of products has been drawn. The geometry representation, i.e. parametric or polygonal, and the interaction methods have been taken as metrics to categorize previous works. Weak connections between the modeling paradigm implemented and the interaction methods, lack of spatial faithfulness, ergonomic concerns and the need for quantitative metrics to compare objectively the data resulting from different testing sessions across the various studies are the main issues identified. In order to get concrete evidence of such thoughts, an experimental session has been devised with users from different backgrounds. They were asked to make conceptual sketches of a computer mouse in a traditional fashion, i.e. with pen and paper, and using two off-the-shelf Virtual Reality applications, based on 3D sketching and 3D sculpting respectively. The results are discussed qualitatively by visually comparing the sketches made by the testers, enriched by information deducted by surveying the users before and after the experiments. By comparing the sketches made by each user with the three procedures, preliminary results indicate that VR systems don't bring dramatic improvements compared to traditional 2D sketching tools. Furthermore, despite being enjoyable, VR systems caused physical fatigue, which is a problem that basically does not affect 2D sketching. Despite the size of the sample cannot provide statistical evidence, the outcomes provided good indications about the technology readiness level of Virtual Reality as a conceptual design tool, paving the way for future research directions.

Keywords: conceptual design, virtual reality, product design

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1 INTRODUCTION

For a few decades, CAD has become a widely established tool that serves a great variety of activities taking place across the product development process. Regardless of any specific category of product, the idea of generating its digital representation is essential to achieve a properly integrated workflow from the initial conceptualization to more downstream development stages, such as performance evaluations, simulations (e.g. finite element analysis or computational fluid dynamics simulation) or manufacturing related aspects.

Scientific literature agreed on defining conceptual design as the phase, in the early product design development, when ideas (innovative or not, feasible or not) are generated to fulfill certain user and project requirements. According to Pahl and Beitz [19], the conceptual design is that stage of the development process that determines the principle solution. It usually follows the planning and task clarification stage, which provides the specification of information as a list of requirements to be satisfied and constraints to be observed. Similar ideas are reported by Ulrich and Eppinger [25], Roozenburg et. al. [23] and Cross [7] , just to name a few. The common stream that animated those studies has been driven by the attempt to figure out, in a systematic way, the framework in which designers and engineers usually operate, breaking down the product development process into well-defined steps and identify what are the inputs and outputs for each of them.

Depending on the field of reference, conceptual design may unfold in the form of flow charts or circuit diagrams. Alternatively, it can imply the necessity of sketching, when graphic representations like drawings are more effective in conveying ideas. This is particularly true in the field of product design, where technically relevant problems do need be taken into consideration, but in most cases have to be sorted in such a way that other kinds of requirements, e.g. aesthetic, are also fulfilled. Figure 1 shows two conceptual design sketches of a blender elaborated by students of the Design School of Politecnico di Milano. It's easy to imagine that when aesthetic considerations are involved, there's no better way than sketching to convey the visual representation of the potential solution.

In more recent times, CAD has established itself as the main set of digital tools to streamline the development process with regards to product design, but its rigidity has historically been a limiting factor in relation

(a) (b)

Figure 1: Two examples of conceptual design of a blender drawn by students from the Design & Engineering Master of Science at Politecnico di Milano

to those initial stages when a discrete degree of uncertainty is welcome [22]. Robertson and Radcliffe in [22] took a survey of 212 experienced engineering designers (88% had a minimum of 4 of experience). On average, most of the users use free-hand sketches when the ideas are being generated (called "immature design" in the survey) even though they agreed on the fact that CAD is a powerful means for visualization and communication. Most frequently, the main reason lies in the fact that CAD packages have been built in order to be operated through a cognitive approach [12], meaning that inputs and parameters need to be made explicit in a rigorous way to generate shapes in the virtual workspace while avoiding potential ambiguities. Clearly, this methodology works well for the embodiment and detail design stages but is not suited for fast, flexible representations, when the designer's main goal is to sketch an idea with the least amount of constraints, as he/she would normally do by drawing freely on a piece of paper.

The question is, how is it possible to translate in digital form the generation of unconstrained, graphic representations, possibly stepping up from the bi-dimensionality of a drawing board to the three-dimensionality of the intended products? Many researchers have been proposing a wide range of innovative techniques to take advantage of recent technological developments. Most commonly the focus has been oriented towards the generation of immersive user experiences where the designer is able to digitally sketch up or sculpt his/her own ideas inside a virtual environment. In theory, this is a very enticing perspective, and it may well become an established modeling paradigm starting from the near future. So far, there seems to be a common agreement between those researchers that are willing to finally overcome the limitations of traditional hardware setups based on 2D visualization and interaction systems.

Firstly, traditional screen panels come with the obvious limitation of a physically restricted digital workspace, that in turn is displayed as a flat projection of an inherently three-dimensional environment. Moreover, hardware tools such as digital drawing boards are good in replicating the activity of traditional drawing, though they don't add much in terms of actual integration within the general workflow. At the same time, when applied to three-dimensional shape generation and manipulation, it's clearly evident that navigating and operating the digital workspace through traditional input devices - namely keyboards and mice - can be cumbersome, and it's one of the main reasons why CAD software tends to be quite demanding with reference to mental stress. Immersive experiences are very promising alternatives, since they have the potential to restore more natural visualization and interaction systems.

Throughout this research study, a resume of the state of the art related to innovative approaches that are oriented to conceptual modeling in the industrial design field is provided. Starting from the analysis of various scientific papers proposing new methodologies and systems, a discussion has been conducted to try explaining why they still struggle to be implemented in real contexts workflows. Modeling paradigms and testing protocols concerns are argued, in the sense that the rapid technological growth in quantitative terms of hardware and software systems hasn't been paired by the establishment of clearly defined methodologies. This makes assessing the outcomes of different research studies in a reliable way extremely hard, if not impossible: qualitative and/or subjective considerations are the most used metric in this domain. In the attempt to overcome such inconsistencies, the traditional sketching methodology, based on the use of pencils and paper has been compared with two, very different VR applications. In this context, testers were asked to reproduce the shape of a computer mouse. It's important to point out that the sample analyzed so far is way too small to draw any definitive conclusion, though it provides useful insights when trying to define future research directions.

2 STATE OF THE ART

The state of the art about technologies that support conceptual design should take into consideration at least two distinct aspects, that are the modeling paradigm and the interaction modality. The latter is strongly dependent on the visualization media: in this paper, the main focus is about VR environments for conceptual design, hence the interaction modalities here considered are the ones enabled by such technologies. Despite interaction and modeling paradigms seem to be distinct aspects, they influence one another.

In [17], an application to model NURBS within a 3D Virtual environment by modifying their target points has been proposed. The prompts are provided through a wand device to operate NURBS-based geometries. The examples provided by the authors are suitable and compliant with the range of application that product designers usually deal with. However, no tests with users were reported to validate the effectiveness of the approach. Using the same interaction approach, a virtual design system, namely VirDe, has been presented in [13]. Despite the VirDe system has been designed targeting CAD and Finite Element Analysis, it provides useful insights about the use of feature-based CAD in a VR environment. In this system, the user provides inputs through a wand device (i.e. FlyStick) and generates solid and surface features while mirroring the same logic of traditional feature-based CAD. The authors reported some complaints for the user interaction with the VR system, mostly related to the shape and the weight of the wand. More recent works continued with the attempt of porting the ordinary features of CAD tools inside immersive environments frameworks. Mine et al. [18] worked on integrating some functionalities included in the CAD software SketchUp (www.sketchup.com) into a VR environment providing inputs through a custom-built controller integrated with a smartphone. The virtual environment was displayed on a large stereoscopic screen. However, the authors do not report any test with potential users. Feeman et al. [9] have transferred the core features of a popular modeling application - Autodesk Fusion 360 - in a VR environment controlled through commercial VR joysticks. The application has been tested by asking the users to generate 3D models of simple, regular geometries. The average number of features and the rate at which the testers added features to the model were taken as the main metrics to indicate the efficiency of the system, while creativity was judged qualitatively by eleven blinded judges. The statistical significance of the results has not been reported, though the authors claim increased enjoyment and potential for accelerated creativity and ideation and a more realistic sense of scale. Despite modeling in real scale with digital models is relatively less important than getting the correct proportions, Air-Modelling [3] switches from VR to an Augmented Reality system focusing on generating simple solid geometries to be displayed in the context of a real environment, so that the dimensions, proportions and positions of the 3D shapes can be verified in real time. The authors claim an average reduction of 44% on the modeling time in 76% of the cases. The interaction in the AR environments is made possible by using hands to trigger a set of codified gestures. The geometries used during the testing sessions are regular and simple and the system has been compared with a feature-based CAD software (i.e. Solidworks). The time savings are mainly due to the fact that the user, using Solidworks, must perform many steps to create a simple geometry body (e.g. input the exact geometry), highlighting the limitations of current feature-based CAD tools for conceptual design. In fact, they were conceived for later stages across the product development process, and the comparison should not be made taking such tools as baseline.

In the systems presented so far, the geometry of the objects was always described as a parametric entity, regardless of being described through surfaces or as solid volumes. Other approaches propose mesh-based representations, while adopting similar interaction strategies. For example, Proto-TAI++ [20] proposes a mesh-based representation of bidimensional, simple thin shapes to be drawn on a tablet and assembled in the 3D space by means of a physical proxy which reflects their position and orientation. Albeit their work focused on 3D assemblies, it provides useful insights to reuse this strategy for modeling as well. SurfaceBrush [24] presents a modeling interface derived from the more popular TiltBrush application (https://www.tiltbrush.com/), and is supported by a specialized surfacing algorithm that converts raw artistic strokes into manifold, meshed surfaces. The results were evaluated with observational methods, preventing any consideration on how effective the system is for product designer. Other works focus instead on finding suitable interaction devices for VR and conceptual modeling. Mockup builder [1] is a system that recognizes the position of the user's fingers through special devices to be worn as rings, in order to draw simple flat shapes on a multi-touch, stereoscopic panel, so that they can be later extruded in the third dimension. Another approach is the one proposed by Fuge et al. [10], where custom built data gloves are used to draw point clouds in space that are later converted into surface geometries. Hummels et al. [12] implemented a gesture based interaction system where their meaning were established by involving designers in explorative experiments. On the same wavelength, Kang et al. [15] studied the minimum set of commands that are necessary for 3D conceptual design based on CSG. The hand-gesture set generated have been then implemented in a rule-based intelligent user interface. In the works by Cohen et al. [6], Cui et al. [8] and Bordegoni et al. [5] a bare hand recognition system has been implemented by means of a Leap Motion device. In the first study, the system allows to virtually pick and move in the 3D space the control points of NURBS curves and surfaces through a natural gestures interface. The second one aims to apply the same kind of interactions within the workflow of traditional mesh-based modeling applications (e.g. Autodesk Maya). In the third one, the goal is to virtually edit 3D geometries that have been previously extracted by scanning physical products, while reproducing through a mechanized metallic strip the curvature of the target surface along a given cross-section.

One of the latest trends seems to push the extensive use of computational tools to correct and overcome the difficulties to reach high level of realism in comparison with the traditional experience of sketching on paper. One example is reported in [11], where the authors present an application in which user generated 3D sketches are digitally beautified by a dedicated algorithm and converted into simple shapes to be assembled together.

Besides the scientific research, several software houses also provided their contribution in the development of VR applications for conceptual design. In recent years, new generation applications have been distributed and made available for a wide plethora of users. This can be intended as a signal that the whole field has got mature enough to be marketed. Notable examples are Gravity Sketch (www.gravitysketch.com/), that arose as a EU funded project, and Kodon (www.tenklabs.com/kodon). The former implements an immersive VR environment where the user can directly sketch in a 3D environment using lines or even NURBS surfaces managed by commercially available VR controllers (e.g. HTC, Oculus), whereas the latter implements a sculpting modeling paradigm to be operated with similar hardware. Both these software tools will be presented in depth and tested later.

Other, more established software houses, such as Dassault Systemes and their 3D Experience suite, propose conceptual design tools as plug-ins for their products, making the integration with the whole product development process more streamlined. To the authors' knowledge, none of them provides such services within a Virtual Reality environment, with advanced interaction devices and with the possibility to sketch directly inside an immersive workspace.

From the state of the art presented so far, it is possible to make a distinction between the different approaches based on the modeling paradigms and the input methods. Regarding paradigms, a classification can be proposed on the basis of how the digital structure of the produced data is translated into visible and editable geometry. On one hand, traditional CAD-inspired workflows aim to retain a parametric approach and its underlying semantic (features, history trees, etc.) when switching to immersive user experiences. On the other, mesh-based representations allow for a higher level of freedom and shape manipulations, especially when managing organic geometries based on free forms. The trade-off here lies in the inability to store the models metadata and the respective parameters. Regarding the input methods, a clear distinction is necessary to gather substantially different categories such as tracking devices (controllers, data gloves, etc.) and software operational logics (based on free gestures, or a pre-defined gesture grammar, etc.) in a coherent way. Grounding on this set of terms, it's possible to sum up the contributions as presented in Table 1. In this case, a first level distinction is made according to the nature of the tracked objects to be used as input devices. They can either be stand-alone controllers, often resembling pens, wands or remotes, or hand tracking systems, such as data gloves or optical sensors allowing bare hands recognition. Moreover, considerations involving the implementation of voice commands have been ignored, since they are not considered strictly relevant in the context of an analysis of the interactions that is inherently related to their spatial deployment.

		INPUT METHODS			
		STANDALONE DEVICES		HAND TRACKING	
		Sticks	Joysticks	Gloves/Rings	Bare hands
GEOMETRY REPRESENTATION	Parametric	[3], [13], [17], [18]	[9], GravitySketch	[1], [10]	[6], [12], [15]
	Mesh	[20]	[24], Kodon		[5], [8], [11]

Table 1: Classification of immersive systems for conceptual design.

2.1 Discussion about the State of the Art

Most of the aforementioned approaches, even the ones pursued by commercial software, still struggle to spread among the designers community and within their everyday routines. There could be several reasons behind that and the following discussion highlights some points based both on the state of the art and on anecdotal evidence.

Analyzing the papers reported in Table 1, some aspects about the protocols adopted for testing such applications are worthy of attention. The main concern regards the test objects oftentimes chosen to be replicated with the developed tools, whatever they are. All the papers cited so far are based on the evaluation of primitive shapes (e.g. cubes, cylinders, etc.) or very simple and regular objects (e.g. a chair). This kind of shapes allows the algorithm and the applications to be tested against their functionality, but in turn they provide little feedback concerning their usability in real contexts, where designers have to deal with far more complex geometries.

In fact, potential users (e.g. product or car designers) see no reasons for the adoption of a complex tool, changing their mind to model such elementary objects. However, the geometrical complexity of the test objects should be weighted in relation to the practical feasibility to conduct the test. As a result, testing procedures for most of the studies that have been taken into consideration are hardly comparable between each other, because they are usually benchmarked against traditional modeling applications based on arbitrary metrics - usually time required to accomplish a given set of operations - and with reference to tasks that imply highly different, and often inconsistent levels of complexity. Thus, such tasks are not objectively defined yet, making them not replicable and not meaningful when trying to compare different studies. In these terms, regardless of the number of participants taking part to tests, the significance of the results is also questionable.

At the present day, little effort has been dedicated defining thoroughly the potential and the limits of such tools. Traditional CAD applications have been developed according to rigid sets of mathematical rules, that are deployed in order to rigorously generate, manipulate and deform 3D shapes. The validity of this paradigm is questionable when shifting towards immersive user experiences aimed at conceptual modeling, where a certain level of uncertainty is acceptable, if not preferable. Hence, alternative sets of rules are yet to be codified when referring to these novel approaches. In most cases, it seems reasonable to rethink the user experience from the ground up, which implies a multitude of challenges.

Ergonomy plays a crucial role to quantify the user's satisfaction level, and it can be tackled in an extremely wide variety of ways, depending on how both hardware and software tools are meant to be exploited when interacting within immersive virtual environments. This was typically a minor problem at the time when there was no alternative to building graphic user interfaces (GUIs) that ended up being displayed on regular screen panels and prompts were provided through more traditional input devices. By comparison, the novelty of such technological advancements means that at this point an effective hardware and software combination is far from being established yet.

That said, drafting on a piece of paper is still the most established methodology when it comes to communicating by means of a graphical language the shape and the arrangement of a potential product. In fact, the ability to provide even basic illustrations of 3D objects with such simple tools is innate to all human beings, because unlike other graphical languages, such as textual information, it is not grounded upon a specific learning path that implies the rigorous knowledge of symbols or other artificial superstructures, but rather on the way any person experiences the world around him/her in spacial terms. An interesting demonstration about this is the study by Athavankar [4]: a blindfolded designer was asked to design an object he had in his mind, without access to sketching or any form of visual feedback. The designer was still able to define the shape of the object, its details and colors. It must be noted though that just like any other skill, the communicative power of drawing becomes more effective when one's talent gets properly fostered with continuous exercise, so that advanced techniques can be eventually mastered. But if an idiom can be considered as a set of communication rules purposefully agreed within a limited community of people, drawing techniques like perspective representation or coloring are universal, since their goal is to replicate the perception of - respectively - depth and light in relation to any human being.

A similar theory may regard the activity of sculpting, where spacial faithfulness is potentially better compared to plain drawing, since all three dimensions can be exploited without any distortion. So why isn't it adopted in lieu of sketching during the ideation phase?

Speaking about spacial faithfulness, its greatest limitation lies in the fact that the physical behaviour of a real object - e.g. a mock-up - has to be taken into account at the expense of abstraction: in other words, it's much easier to represent the levitation of an object on paper rather than replicating it through a functional model. This is why most people, including the designers themselves, prefer the immediacy of sketching, since the communicative effectiveness is prioritized higher than the spacial faithfulness at conceptual level. The switch usually occurs in later stages, when for example working principles or aesthetic considerations need to be validated rather than just communicated, at which point abstraction is no longer functional to the development process. In addition to all this, it is clearly apparent from everyone's daily experience that the actual tools to produce a basic draft are much handier than the ones required to sculpt an object.

Digitalization has brought great benefits to traditional sketching too, since nowadays professional applications and dedicated hardware tools (tablets, digital pens, etc.) allow to faithfully replicate strokes, colors and layers on virtual canvases. In spite of this, a radical breakthrough has never taken place in this field, since the general approach towards the sketching activity is broadly the same in terms of interactions compared to older, more analog counterparts relying on pencils, markers and paper sheets.

Theoretically, mid-air 3D sketching is one of the most enticing candidate techniques to provide a significant leap among state of the art solutions. The core principle consists of the ability for the user to sketch, or more generally to produce visible strokes, within a 3D immersive environment and through natural gestures interfaces. Apparently then, this sounds similar to regular 2D sketching, with the only evident difference that the third dimension is completely unlocked when considering the available workspace. Given these premises, 3D sketching can only take place within a digital environment, most often implying Virtual or Augmented Reality tools, meaning on the plus side that the only limit to achieve perfect spacial faithfulness for a 3D design lies exclusively in the ability of the user. An important consideration to make though is that it takes just a few minutes of training with one of the off-the-shelf applications to realize that the general approach in terms of interactions is actually much different compared to traditional drawing. Actually, Wiese et. al. [26] reported encouraging results about the short term learnability curve for mid-air sketching tool. Despite sounding convenient, such conditions imply that the drawing approach from the user's point of view needs to be switched abruptly, because perceptual-motor skills have to be re-calibrated in ways that are new to most people. Also, dedicated hardware and software tools need to be adopted, thus impacting significantly on the number of potential users.

An interesting alternative to 3D sketching is represented by sculpting applications for VR environments. The general idea is focused on recreating the activity of clay modeling within a 3D immersive environment, providing to the user a variety of simulated tools to add or subtract material or perform refinement operations such as local smoothing. Despite the fact that this category of software is generally advertised towards the digital artists community, it definitely deserves attention from a product design standpoint, since it aims to represent the digital counterpart of physical clay modeling, that is an iterative activity occupying a very relevant spot in the product development process, especially at conceptual level.

Transferring this whole methodology in a virtual, visually immersive environment immediately implies the fact that the user gets rid of some very evident limitations concerning the real world alternative, whose purpose is generally oriented to the validation in a real world scenario of upstream design activities, usually in terms of aesthetic considerations. In other words, the ideation phase rarely involves the generation of real, 3D mock-ups from the very start, but rather mock-ups are the means used by designers to condensate in a physically tangible object all the assumptions that have been made in previous stages through sketches and preliminary digital 3D models.

Such considerations seem promising, and are the most relevant reason why it is worth questioning if digital clay modeling can be shifted from being a validation oriented activity to an ideation oriented one. The quality of the available interactions is the biggest concern at this point, because bringing such an activity from a real to a virtual scenario implies a major trade-off that has to be investigated: the lack of any haptic feedback that can effectively simulate the sensation of touching and shaping clay.

In comparison to 3D sketching, where the output strokes only represent visual entities that are not supposed to possess any weight in a material sense, the idea of directly shaping virtual volumes while operating in a totally empty space can be a critical drawback to usability [2].

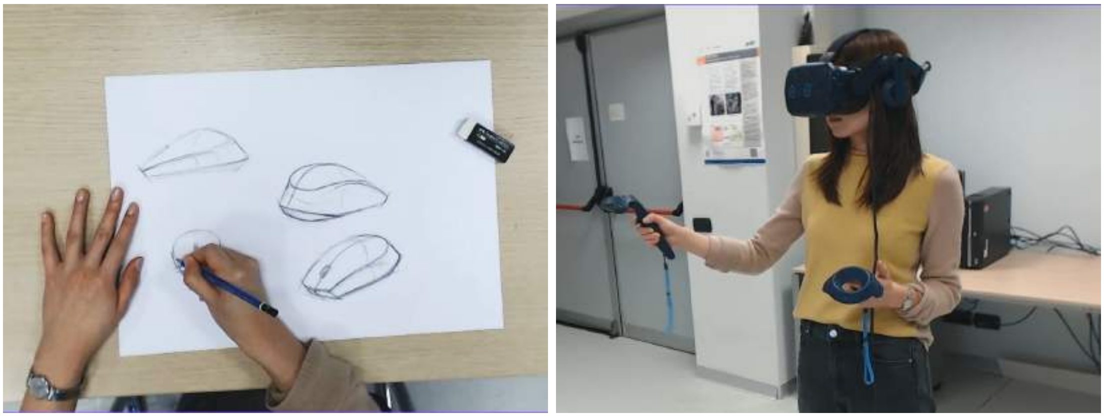
3 SYSTEM SETUP, TESTS AND DISCUSSION OF THE PRELIMINARY RESULTS

In the following section a testing protocol to compare the three methodologies mentioned above is proposed. Based on few sample results that have been collected, it's been possible to understand some crucial points that could not be foreseen in advance with regards to the organization of the activities. Such considerations may eventually prove relevant once the test is actually conducted on a larger sample of users. At the present day though, it's not been possible to achieve a sufficient level of statistical significance, meaning that the ultimate goal of the present testing procedure is aimed, first and foremost, at establishing a reliable protocol when trying to compare different shape generation methodologies like the ones previously listed.

The test has involved a sample of 3 people so far, with educational backgrounds spanning from Mechanical Engineering to Product Design. An important aspect to point out regards the fact that basic interaction approaches represent the main subject of the test, which means that when taking into consideration the digital systems, only a number of core features have been made available to the users. In this way, it is possible to reduce the training time to a few minutes for each tester, regardless of their drawing or modeling skills.

3.1 Hardware and Software Configuration

In relation to the chosen methods and tools that have been adopted when referring to the three methodologies, for 2D sketching the testers will only have to deal with a common sheet of paper, a pencil and an eraser, as shown in Figure 2a. Digital 2D sketching systems based on tablets were also considered, but the simple fact that they require a minimum level of expertise to operate correctly the user interfaces was a deal breaker, especially in relation to those testers that do not have a design background and are less likely to have ever worked with such hardware and software setups.



(a) (b)

Figure 2: (a) Tester involved in the 2D sketching activity and (b) tester wearing an HTC Vive Pro device and holding controllers while operating in the VR environments

The 3D sketching system that has been chosen is based on an HTC Vive Pro device, operated through a pair of controllers included in the official bundle and connected to a workstation PC, as shown in Figure 2b. As anticipated, Gravity Sketch is the application tested. Its core feature consists of the possibility to produce virtual strokes in a VR environment through natural gestures and without spacial limitations. More advanced operations, such as curves and surfaces generation or fine control points editing are also implemented, making this software one of the most interesting proposals towards the product designers community. For the purpose of this test though, in order to simplify as much as possible the workflow while focusing on the usability at the level of interaction systems, the testers will only be allowed to use the stroke feature in addition to basic position manipulations of the virtual items, with the final aim to achieve a wireframe-like representation.

In relation to 3D sculpting, the hardware system is identical to the one that's been used to test 3D sketching, with the only difference that the software used this time is Kodon. There are two possible methodologies through which it can be operated. On one side it is possible to manipulate and edit mesh geometries by dragging vertexes in space. This approach is very similar to what is already possible with more established applications such as Autodesk Maya or Blender, with the advantage for the user of being able to work in an immersive environment enabled by VR. On the other side, the system allows to operate a digital toolkit to replicate through natural gestures the clay modeling activity while producing voxel based geometries. The latter is definitely the more interesting of the two with regards to this research work, since it represents a more radical approach involving direct shape generation and editing. Additive, subtractive and smoothing tools are available, in addition to a variety of more sophisticated features that in any case will not be considered in the testing process to keep the workflow easy.

3.2 Task and target Model

The testers were asked to reproduce in the most faithful way possible - according to their own skills - the main design features of a typical industrial design product, namely a Logitech M330 Silent Plus mouse as the one shown in Figure 3. The choice of this object is due to the fact that it's designed to satisfy both ergonomic and aesthetic requirements, meaning that its appearance is strongly characterized by few, yet very distinctive curves that flow along the main surfaces while developing in all three dimensions. Furthermore, its compact size makes it very easy to manipulate and observe. All users tested the 3 available approaches in each session

Figure 3: Front and back views of the Logitech M330 Silent Plus mouse; the defining lines are highlighted in bright colors

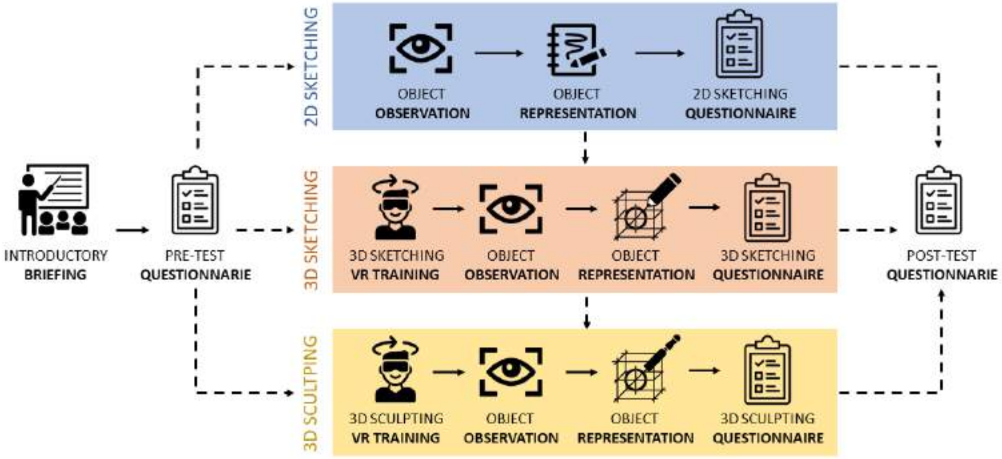


Figure 4: Test execution scheme; the order of the methodologies adopted by each user has been randomized.

and the testing procedure was organized as shown in Figure 4:

1. Each user was asked to fill a form where questions such as their age, the educational background, how often he/she uses sketches in the professional life and previous experience with digital tools for conceptual design were taken for the record.
2. For the sessions involving Gravity Sketch and Kodon, each user was introduced to the main software features he/she was allowed to use in the context of a short training session. Then, the tester has been left free to play around with the commands for the time needed to get acquainted with the software features.
3. Before starting with each approach, the user was given the object for 10 minutes, in order to let him/her memorize the most relevant design features.
4. At this point, the tester has been asked to produce a conceptual representation of the mouse, without any time constraint. The tester has been left free to decide when he/she was completely satisfied with the result.
5. After focusing on one methodology, testers were asked to fill a form to describe their experience in terms of ease of use of the system adopted, enjoyment, physical stress and satisfaction about the results.

6. A final, more general questionnaire was proposed to the users to rate the overall experience.

The testing sequence was randomized for each session, to limit the fact that shifting from one methodology to the next, the user supposedly learns more and more details about the object to replicate, and acquires more confidence with the tools, especially the digital ones that require a minimum level of training.

Since most people do not have any experience with the type of device and software employed, the training session with the VR tools was fundamental. The user is then left free to decide when to start with the actual test: for the records, it never took more than 15 minutes to acquire a decent level of confidence.

Regarding the step 3, there is a crucial difference between having the object available during the test and keeping it away, only relying on memory skills. The idea of replicating a shape that has been previously fixed in mind is a process that resembles more the ideation stage, where no physical reference exists yet. Secondly, it is pretty evident that VR applications cannot be operated while simultaneously keeping an eye in the real world. Plus, placing a rendering of the object within the virtual scene may compromise the immersivity.

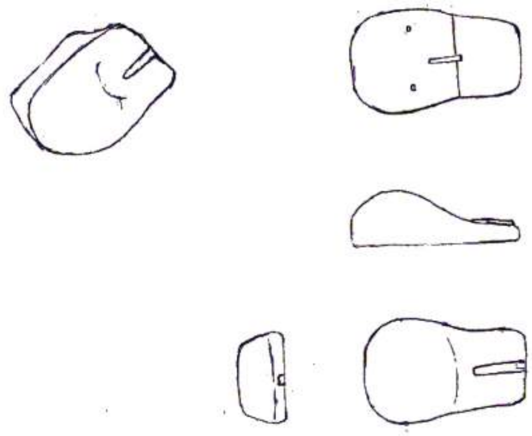
About not giving specific time constraints to complete the tasks, the motivation lies in the fact that the design features to represent were relatively few and putting restrictions in these terms could affect to some extent the quality of the outcomes, which is ultimately the main aspect to be assessed. Moreover, in this way, the user does not feel any kind of pressure. Finally, each session was video recorded for further investigation and to keep track of the working time.

3.3 Discussion of the results

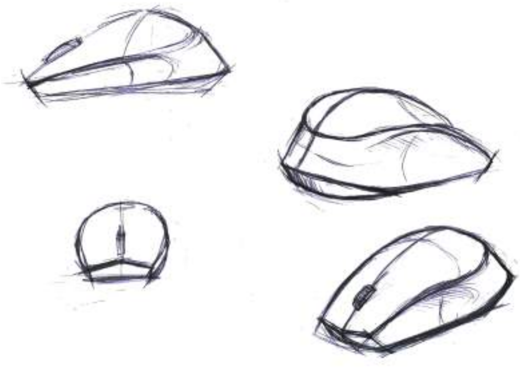
In the context of the present article, 2D sketching has been considered as the main benchmark, and all the outcomes have been evaluated at the present state of the work on the basis of qualitative considerations. Figure 5 shows the two extremities for the handmade sketches. The sketches in Figure 5a and 5b have been made by a mechanical engineer and a product designer respectively. Unsurprisingly, the educational background plays a major role with regards to the faithfulness of the representations in relation to the real object. Testers coming from a Mechanical Engineering education produced more essential sketches and models in terms of details and resemblance to the original object, regardless of the tools that had been adopted. Furthermore, in their case it's been observed an interesting tendency to provide most of the details in the 2D sketches by means of orthogonal views.

Figure 6 and Figure 7 show the two extremities for the sketches made with GravitySKetch and Kodon respectively. On the left of each of those figures, the results come from a mechanical engineer, while the figure on the right shows the sketches made by a product designer. This trend seems to be consistent throughout each session, where VR tools themselves do not dramatically improve the quality of the results compared to traditional 2D sketching. It must be considered though that none of the testers had any form of prior experience with them, but generally speaking, the tester with a higher level of drawing skills on traditional sketching was able to produce equally good results by means of VR tools. VR tools then did not seem to enable dramatic improvements on the overall quality of the sketch. The evidence so far was that the only user coming from a product design background had the most developed skills across all the three methodologies in relation to what had been asked, finding the overall experience with VR tools highly enjoyable. Furthermore, the works by the product designer provided the highest level of realism and respect of proportions (Figures 5b, 6b and 7b). 3D sculpting, despite being very enjoyable according to all testers, was the most critical approach among the three. There were complains about the inability to have a fine control of the inputs, underlining why such systems are well suited towards highly skilled digital artists that are able to exploit their features, but can be frustrating to users that are approaching this technique for the first time, leading to a generally low satisfaction level about the final results. 3D sketching was then a better compromise, being the strokes more manageable than additions or subtractions of virtual material.

Defining metrics is one of the most critically lacking aspects in relation to the tests conducted so far in this research field. A comprehensive reviews of them has been proposed by Joshi and Summer [14]. Some of

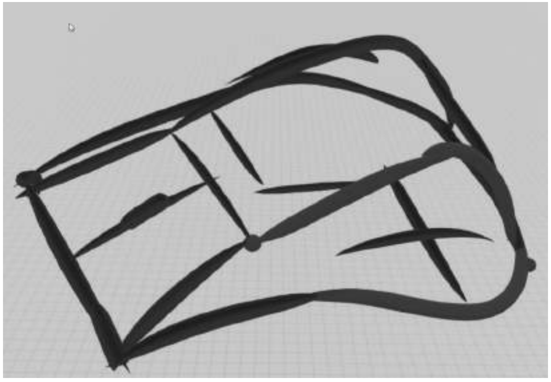


(a)

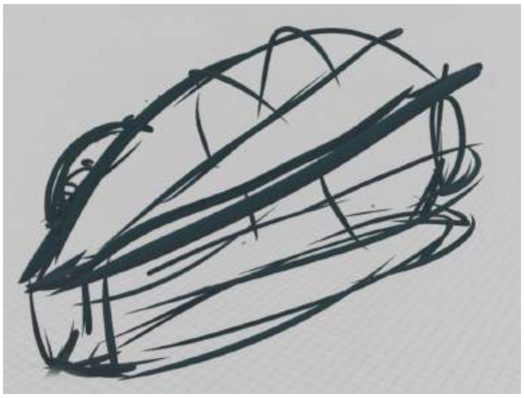


(b)

Figure 5: Examples of 2D sketches by a Mechanical Engineer (left) and an Industrial Designer (right)

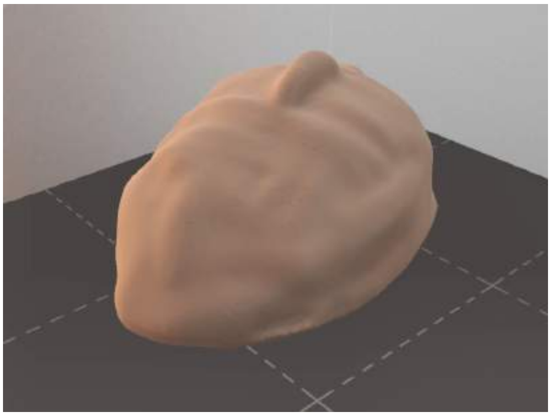


(a)

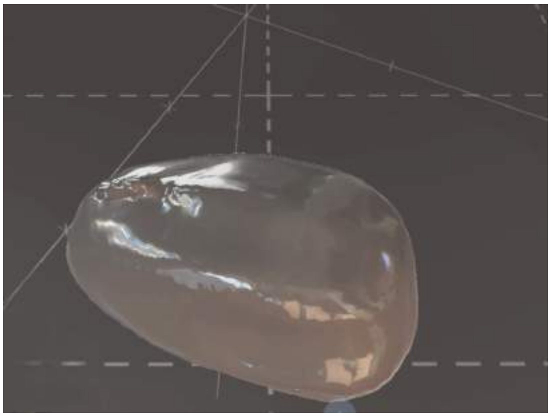


(b)

Figure 6: Examples of 3D sketches by a Mechanical Engineer (left) and an Industrial Designer (right)



(a)



(b)

Figure 7: Examples of sculpted 3D models by a Mechanical Engineer (left) and an Industrial Designer (right)

the most adopted quantitative metrics are the sketch count made in a specific time frame as well as the size and the scale of the same. Among the quantitative metrics also appears the quality, that is a tricky concept to define objectively. However, according to [16], it can be described according to the perspective, media, light, line weight, overall ID Style and so on and so forth. Despite some of them can be measured quantitatively, the authors in [16] asked to assign a score for each of the categories to six professional designers. In fact, assigning numerical values to express, for example, which is the correct line weight implies, in turn, a subjective evaluation by the tester. Furthermore, to the authors' knowledge, no metrics for evaluating 3D sketches (i.e. sketches or models made in a 3D space) have been proposed yet: this is also understandable because of the novelties this technologies represents. Measuring quality in a reliable, objective way is not an easy feat, but a larger sample than the one presented here is needed to indicate the way to follow and the parameters to consider. Despite the three tests do not allow to achieve a sufficient level of statistical evidence neither to define a new metric, it is already evident at this point that the evaluation of the results needs to be normalized throughout the three methodologies for each tester, because educational backgrounds and pre-existing drawing skills tend to vary across a very wide range, making it impossible - if not pointless - to rank the outcomes across an absolute scale.

Regarding the time spent to obtain the final results, while traditional 2D sketching only took around 10 minutes for each tester, the production of satisfying results using VR tools was a much slower process, ranging between 20 and 40 minutes. In most cases, this led to physical fatigue at the end of each session, suggesting that splitting the test into more intervals can prove beneficial to reduce stress and, consequently, improve the quality of the results. It also suggests that the ergonomy of the process should be deeply investigated, writing down rules to teach the proper use of these devices. This is especially true for operational contexts where people would spend a major part of their working routine dealing with this sort of design tools.

4 CONCLUSIONS

In this research study, Section 2 has been dedicated to list and analyze a number of previous works that have been published in recent years as scientific papers proposing innovative systems oriented to conceptual representations for the domains of Design and Engineering. After providing definitions to frame the meaning of conceptual design, it's been observed that the range of approaches and methodologies proposed is very wide, meaning that in relatively little time many different ideas have arisen on the wave of fast developing hardware and software technologies. On the other hand, this scenario has led to the lack of a truly established catalog of ideal setups. In other words, figuring out the full potential of these systems in relation to realistic use cases is still a very hard task. In our opinion, this partially explains why such solutions are still far from being considered mainstream.

When focusing on the product development process though, a tool able to produce 3D models ready to be used as input files for downstream design activities is a necessary brick to pursue the complete digitalization of the product development process. Besides the methods focusing on translating 2D sketching into 3D models, the ability for the designers to directly sketch in a 3D world is certainly a research direction worth to bet on. Some studies have committed to porting operations of traditional CAD workflows towards immersive user experiences based on Virtual or Augmented Reality. In other cases, free modeling systems have been implemented to be operated with similar tools, fulfilling in a more effective way those requirements that are expected by a conceptual modeling platform. Also, commercially available applications based on VR have started to become available, showing how the technology is mature enough to achieve commercial success.

The main issue related to the analysis of prior research work is the lack of a clearly established protocol to assess the significance of the results in those cases where testing sessions have been devised. This makes particularly hard to compare different methodologies adopted among various studies.

Section 3 reports the experiments carried out with two off-the-shelf VR tools. The aim was to setup an experiment to figure out whether and how VR-based 3D sketching and 3D sculpting are beneficial compared to traditional 2D sketching. A testing protocol has been developed and checked on a small sample of users made of three people coming from Product Design and Mechanical Engineering backgrounds. Preliminary results indicate that VR systems don't bring dramatic improvements compared to traditional 2D sketching tools in terms of quality of the outcomes, meaning that the level of skills has been consistent across all the three methodologies for each tester, with an evident superiority of the works by the only designer that took part to the experiment. In general, it's been reported that despite being enjoyable, such VR systems are still prone to cause fatigue after short periods of time, which is a problem that basically does not affect 2D sketching.

Further, deeper testing is needed to orient future research directions in relation to this field, in order to achieve a sufficient level of statistical significance while providing meaningful insights. Since "innovation" includes both the application of scientific advancements or other types of research, but also improved way of doing a process [21], we think that "technically" the technologies are mature enough to be brought to professional level, so the research should be directed more on how to fulfill the requirements for the industry professionals.

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REFERENCES

[1] Araújo, B.R.D.; Casiez, G.; Jorge, J.A.; Hachet, M.: Mockup builder: 3d modeling on and above the surface. Computers & Graphics, 37(3), 165–178, 2013. http://doi.org/10.1016/j.cag.2012.12.005.

[2] Arora, R.; Kazi, R.H.; Anderson, F.; Grossman, T.; Singh, K.; Fitzmaurice, G.: Experimental evaluation of sketching on surfaces in VR. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems. ACM, 2017. http://doi.org/10.1145/3025453.3025474.

[3] Arroyave-Tobón, S.; Osorio-Gómez, G.; Cardona-McCormick, J.F.: AIR-MODELLING: A tool for gesture-based solid modelling in context during early design stages in AR environments. Computers in Industry, 66, 73–81, 2015. http://doi.org/10.1016/j.compind.2014.10.007.

[4] Athavankar, U.; Mukherjee, A.: Blindfolded classroom: Getting design students to use mental imagery. In Human Behaviour in Design, 111–120. Springer Berlin Heidelberg, 2003. http://doi.org/10.1007/978-3-662-07811-2_12.

[5] Bordegoni, M.; Covarrubias, M.; Caruso, G.; Cugini, U.: Freehand gesture and tactile interaction for shape design. Journal of Computing and Information Science in Engineering, 16(4), 2016. http://doi.org/10.1115/1.4033230.

[6] Cohen, M.; Regazzoni, D.; Vrubel, C.: A 3d virtual sketching system using NURBS surfaces and leap motion controller. Computer-Aided Design and Applications, 17(1), 167–177, 2019. http://doi.org/10.14733/cadaps.2020.167-177.

[7] Cross, N.: Engineering design methods: strategies for product design. John Wiley & Sons Inc, 2000.

[8] Cui, J.; Sourin, A.: Mid-air interaction with optical tracking for 3d modeling. Computers & Graphics, 74, 1–11, 2018. http://doi.org/10.1016/j.cag.2018.04.004.

[9] Feeman, S.M.; Wright, L.B.; Salmon, J.L.: Exploration and evaluation of CAD modeling in virtual reality. Computer-Aided Design and Applications, 15(6), 892–904, 2018. http://doi.org/10.1080/16864360.2018.1462570.

[10] Fuge, M.; Yumer, M.E.; Orbay, G.; Kara, L.B.: Conceptual design and modification of freeform surfaces using dual shape representations in augmented reality environments. Computer-Aided Design, 44(10), 1020–1032, 2012. http://doi.org/10.1016/j.cad.2011.05.009.

[11] Huang, J.; Rai, R.: Conceptual three-dimensional modeling using intuitive gesture-based midair three-dimensional sketching technique. Journal of Computing and Information Science in Engineering, 18(4), 2018. http://doi.org/10.1115/1.4040982.

[12] Hummels, C.; Paalder, A.; Overbeeke, C.; Stappers, P.; Smets, G.: Two-handed gesture-based car styling in a virtual environment. In 30th International Symposium on Automotive Technology & Automation, vol. 1, 227–234. Automotive Automation Ltd., 1997.

[13] Ingrassia, T.; Cappello, F.: VirDe: a new virtual reality design approach. International Journal on Interactive Design and Manufacturing, 3(1), 1–11, 2008. http://doi.org/10.1007/s12008-008-0056-2.

[14] Joshi, S.; Summers, J.D.: Representation: Metrics for analyzing sketches - a critical survey. In Volume 7: 9th International Conference on Design Education & 24th International Conference on Design Theory and Methodology. American Society of Mechanical Engineers, 2012. http://doi.org/10.1115/detc2012-71425.

[15] Kang, J.; Zhong, K.; Qin, S.; Wang, H.; Wright, D.: Instant 3d design concept generation and visualization by real-time hand gesture recognition. Computers in Industry, 64(7), 785–797, 2013. http://doi.org/10.1016/j.compind.2013.04.012.

[16] Kwon, E.; Camba, J.D.; Kimbrough, M.: Conceptual product design in digital and traditional sketching environments: a comparative exploratory study. Journal of Design Research, 16(2), 131, 2018. http://doi.org/10.1504/jdr.2018.10014195.

[17] KWON, J.; LEE, J.; KIM, H.; JANG, G.; CHAI, Y.: Deforming NURBS surfaces to target curves for immersive VR sketching. IEICE Transactions on Information and Systems, E93-D(1), 167–175, 2010. http://doi.org/10.1587/transinf.e93.d.167.

[18] Mine, M.; Yoganandan, A.; Coffey, D.: Principles, interactions and devices for real-world immersive modeling. Computers & Graphics, 48, 84–98, 2015. http://doi.org/10.1016/j.cag.2015.02.004.

[19] Pahl, G.; Beitz, W.; Feldhusen, J.; Grote, K.H.: Engineering Design: A Systematic Approach. Springer London, 2007. http://doi.org/10.1007/978-1-84628-319-2.

[20] Piya, C.; Vinayak; Ramani, K.: Proto-tai++: Exploring perceptually consistent creation of planar shape assemblies through multimodal tangible interactions. Journal of Computing and Information Science in Engineering, 16(3), 030906, 2016. http://doi.org/10.1115/1.4034266.

[21] Ramilo, R.; Embi, M.R.B.: Critical analysis of key determinants and barriers to digital innovation adoption among architectural organizations. Frontiers of Architectural Research, 3(4), 431–451, 2014. http://doi.org/10.1016/j.foar.2014.06.005.

[22] Robertson, B.; Radcliffe, D.: Impact of CAD tools on creative problem solving in engineering design. Computer-Aided Design, 41(3), 136–146, 2009. http://doi.org/10.1016/j.cad.2008.06.007.

[23] Roozenburg, N.F.; Eekels, J.: Product design: fundamentals and methods, vol. 2. John Wiley & Sons Inc, 1995.

[24] Rosales, E.; Rodriguez, J.; SHEFFER, A.: SurfaceBrush: from virtual reality drawings to manifold

surfaces. ACM Transactions on Graphics, 38(4), 1–15, 2019. http://doi.org/10.1145/3306346.3322970.

[25] Ulrich, K.T.: Product design and development. Tata McGraw-Hill Education, 2003.

[26] Wiese, E.; Israel, J.H.; Meyer, A.; Bongartz, S.: Investigating the learnability of immersive free-hand sketching. In Proceedings of the Seventh Sketch-Based Interfaces and Modeling Symposium, 135–142, 2010.