Virtual Reality in Product Design: Researches between 1997 and 2021

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Article Info	Abstract
	Virtual reality technologies, which provide an interactive and immersive 3D experience and visualization in real size, have currently spread to many fields like gaming, health, education, military, and also product design. Studies about applications of VR technologies in product design have begun to increase from year to year. This study aims to give suggestions about the topics that the next studies can focus on by scanning articles published between 1997 and 2021 systematically according to six macro-categories (early stages, co-design, 3D modeling, virtual assembly and prototyping, mechanical simulation, finite element method (FEM), product evaluation and education) and the technologies (HMD, desktop and CAVE) used which is developed by Berni and Borgianni [4].

1. INTRODUCTION

In order to understand the meaning of virtual reality (VR), it is necessary to define both terms. Virtual is defined as "almost a particular thing or quality" [1] while reality is defined as "a thing that is actually experienced or seen, in contrast to what people might imagine" [2]. Combining the two terms, VR refers to the actual experience of human beings. According to the Collins Dictionary, "the computer-generated simulation of three-dimensional images of an environment or sequence of events that someone using special electronic equipment may view, as on a video screen, and interact with in a seemingly physical way" [3].

Today, VR technologies are widely used in many fields such as gaming, health, education, military industry, with its feature that provides an interactive and immersive 3D experience and visualization in real size. Research on its use in the field of product design has also begun to increase. As a result of the literature research, it is seen that the researchers generally focus on the stages of the design processes of these technologies, their effects on creativity, 3D thinking, product evaluation processes, and therefore on time and cost. These studies indicate that the importance of using VR technologies in product design is increasing. Therefore, the aim of this study is to be a resource about VR technologies and the use of these technologies in the field of product design and to give suggestions about the topics that the next studies can focus on. For this purpose, the literature is presented under the headings of VR's definition, development, classification, current VR applications, and VR in product design. Articles published between 1997 and 2021 were scanned systematically according to six macro-categories (early stages, co-design, 3D modeling, virtual assembly and prototyping, mechanical simulation, finite element method (FEM), product evaluation and education) and the technologies (HMD, desktop and CAVE) used which is developed by Berni and Borgianni [4]. Their densities were determined by visualizing these articles according to their numbers in the mentioned categories.

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2. VIRTUAL REALITY

2.1. Definition of Virtual Reality

VR tries to create a realistic three-dimensional environment in which the user is given the ability to navigate and interact with the created scene [5]. In other words, VR offers solutions that are believable to our senses and include life-like experiences [6]. Persons operating the VR system get the impression that they are in a virtual three-dimensional environment. To give the user the impression of a virtual environment and create an immersive environment, CAVE (short for cave automatic virtual environment) [7], a cubic shaped area of walls that can generate images, or headphones or glasses that place a screen in front of the user's view are used.

Geszten et al. [8] explain that realistic three-dimensional environments are the most suitable environment for users to make detailed exploration and planning because of the similarities that can be found between the way we interact with the real world around us and the possibilities offered in the virtual environment. These three-dimensional digital environments allow users to collaborate with each other remotely, manipulate the environment in ways that would not be possible in the real world, and also gain a hypothetically unlimited space for storing information.

VR offers a way to interact with computers more intuitively and comprehensively than with traditional peripherals such as keyboards, mice and monitors. With VR, the user is directly involved in the experience and can interact with the environment intuitively using their own body. In VR, the user's body becomes a part of the virtual world, so that the user can be more mentally engaged with the system. Most VR systems in use today use a head-mounted display and motion controllers, but in some cases devices such as an omnidirectional treadmill or hand tracking gloves are also used [9, 10]

While VR has a completely computer-generated environment, augmented reality (AR) is created by adding or subtracting computer-generated virtual images to real space [11]. AR provides an understandable and meaningful view by blending virtual and real environments [12]. Mixed reality (MR) is a mixture of virtual and real elements interacting and creating new environments and visualizations together. The term 'extended reality' (XR) is used when talking about VR, AR, and MR as a technology field to bring them all under one term [13, 14]

According to Wang and Schnabel [15], MR has been extended from the real world to the virtual environment. Figure 1 shows the layout from reality to the virtual world.
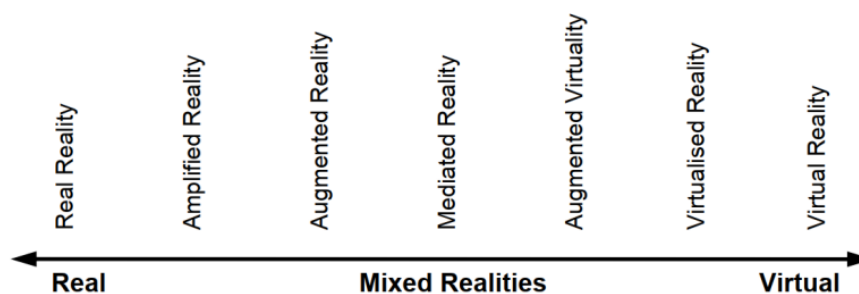
Figure 1. Mixed reality, from reality on the left to virtuality on the right [15]

2.2. Development of Virtual Reality

Although it appears as a new term, the history of VR dates back to the 1950s. In 1957 Morten Heiling designed a large machine called the Sensorama, which was like a large kiosk (Figure 2). The purpose of the machine is to combine several technologies to give the feeling of being completely immersed in a 3D environment. Heiling has added effects such as sound, scent, vibrations and wind to enhance the feeling of immersion in the virtual environment.
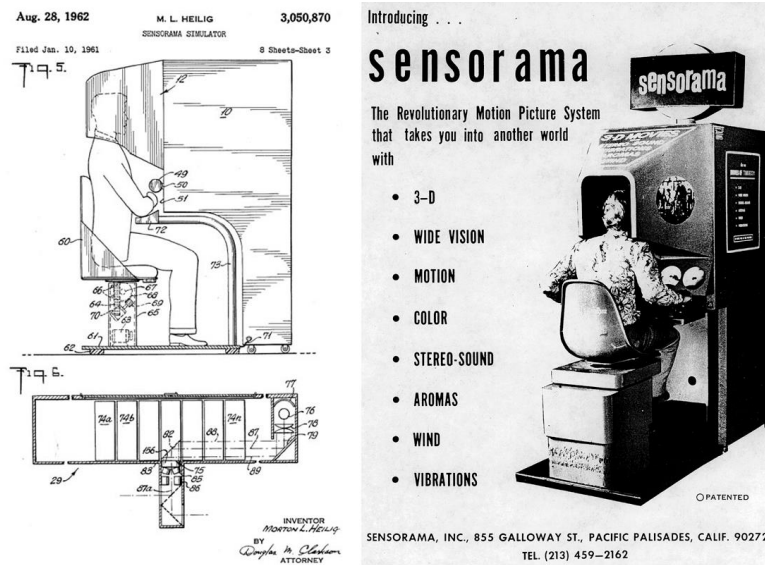
Figure 2. *Sensorama [137]*

Although Heiling developed his invention as the world's first head-mounted display in 1960, the project had to be stopped due to lack of funding. Heiling's invention has been recognized as the basis for the development of VR [16]. Later in the 1960s Headsight, The Ultimate Display and Sword of Damocles head-mounted displays were invented. Although these were large and heavy as the first head-mounted displays, they had similar features with today's displays, such as monitoring the user's head movement [17, 18]. In 1978, a virtual trip was created at the Massachusetts Institute of Technology that included an interactive tour of the city of Aspen using photos taken from a camera mounted on a car driving around the city. This Aspen movie map allowed the user to navigate the city using a computer [19].

In 1982, Thomas Furness created the Visually Coupled Airborne Systems Simulator (VCASS), a virtual flight simulator containing a virtual layer above the real world [20]. In 1987, the term "virtual reality" was coined by Jaron Lanier [21]. In the 1990s, VR technology made progress, especially in the video game industry, with the release of the first VR games, and Nintendo and Sega developed their own VR systems at about the same time. In 2007, Google announced Street View, which allows users to view panoramic images from all over the world. In 2010, a prototype of the Oculus Rift was developed, the most advanced commercial VR technology to date. By 2017, companies such as Google, Apple, Amazon, Sony, and Samsung, in addition to HTC and Oculus, also developed and launched their own VR systems. In 2018 and 2019, mobile VR devices were mostly replaced by wireless, PC-free, stand-alone VR devices. HTC Vive Focus and Oculus Quest are among the most popular VR devices available wirelessly today.

2.3. Classification of Virtual Reality Systems

According to the taxonomy proposed by Muhanna [7] shown in Figure 3, VR systems are classified into three levels according to the degree of immersion. The so-called basic VR systems are the systems with the lowest degree of immersion. VR systems with a higher degree of immersion than the base class are experienced in the class defined as partial immersion VR systems. Finally, the full immersion VR systems have the highest level of immersion.
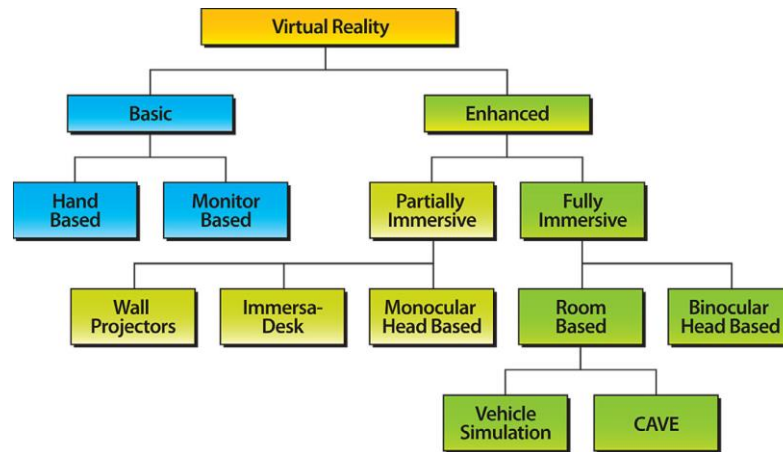
***Figure 3.** Virtual reality systems taxonomy [7]*

Basic VR systems are screen-based, pointer-driven systems that do not require special input or output devices to display a VR environment that is presented with three-dimensional graphics [22]. These systems can be sub-categorized as hand-based and monitor-based VR systems. Hand-held devices such as mobile phones, personal digital assistants, ultra-mobile computers, and portable game consoles are used to provide the VR experience in hand-based VR systems [23]. On the other hand, monitor-based VR systems are basically desktop computers that display three-dimensional graphics on monitors.

Advanced VR systems require more powerful devices than those used in base systems to create a VR experience. Depending on the mental immersion factor, advanced VR systems can be partially or fully immersive. Partially immersive VR systems use a single projector to display a virtual world on a large screen. Participants do not need to wear glasses, as these types of systems do not show scenes in three dimensions. However, it tracks some parts of the body and requires the use of special gloves. Although these gloves give the participant the ability to interact with the VR system, they limit the degrees of freedom [7].

ImmersaDesk is another subcategory of partially immersive VR systems. Participants must wear special glasses in order to see the contents on the projection screen in a three-dimensional experience. The screen provides two overlapping pictures or stereo images of the same content so that each eye of the participant receives the same scene but from a slightly different angle [24]. This gives the participant a sense of the third dimension.

Head-mounted VR systems, another type of VR system, are systems that are worn on the participant's head and provide visual and auditory feedback. These systems can be partial or fully immersive. Monocular head-mounted systems are examples of partial immersive VR and are also considered AR systems. Fully immersive VR systems provide the participant with three-dimensional virtual scenes in a wide field of view. Head-mounted displays [25] as a fully immersive VR system, two small screens display the virtual scene to each participant's eye. In addition to providing a wider field of view, this feature transfers the third dimension to the participant by displaying different content on each screen.

According to the classification of Anthes, García-Hernández, Wiedemann and Kranzlmüller [26], head-mounted displays are divided into two categories as mobile and wired. The mobile subcategory includes bezels developed for smartphones and mobile head-mounted displays. Mobile head-mounted displays are wireless devices that do not need any computer or smartphone (Figure 4).

Figure 4. *Mobile head mounted displays [138] a) Oculus Quest [139]*

Wired head-mounted displays (For example, Oculus Rift and HTC Vive) are devices powered by a powerful computer and 6-degrees-of-freedom (DOF) monitoring system. Apart from systems that promise room-scale experience, it conceptually focuses on sitting use.

Head-mounted displays serve the purpose of completely obscuring the user's visual field to involve the user in a realistically rendered virtual environment or video experience [27]. To achieve this isolation effectively, head-mounted displays are usually in the form of a helmet that is worn directly on the wearer's head. The way head-mounted displays work, constantly presents the visual image to the wearer's eyes in close conjunction with head movements, and what is shown to the user always remains in a specific and relative position to the wearer's eyes and ears [28].

Head-mounted displays work in various ways to interact with the virtual environment. HTC Vive and Oculus Quest use controllers to receive input from users, while other glasses, such as Samsung Gear VR and Hololens, operate using movements of the user's head [29]. Hololens also uses hand gestures as well as head movements. In eye-tracking technologies, which is another form of selection other than control in head-mounted screens, participants can choose using their eyes [29]. Selection can occur at different speeds depending on how long the user has focused on a particular object, also known as dwell time [30].

In the taxonomy they developed, Anthes, García-Hernández, Wiedemann, and Kranzlmüller [26] examine the input devices used for head-mounted displays in three different sub-categories: controls, navigation devices and body tracking systems. Controllers are devices that can be wired or wireless that are handheld and allow input by top-mounted joysticks or touchpads. Navigation devices are used to give the user the illusion of moving in infinite space and to act as an input source to travel in the virtual environment. Conventional treadmills allow movement in one direction, while current developments in VR support movement in a two-dimensional plane.

Posture estimation approaches focus on the actual posture of the user's body or upper body, as well as the movement of the user's hand. Commonly applications use magnetic tracking, some rely on inertial measurement units combined with magnetic tracking. The approaches chosen for motion tracking range from hand-worn strain gauges or data gloves with fiber optics to completely non-contact technologies using optical tracking to wrist-worn technologies using electromyography measurement [26].

The last group in the classification of VR systems are room-based systems. Here, participants get their VR experience in a room. The Cave Automatic Virtual Environment (CAVE) is another example of room-based fully immersive AR systems (Figure 5). The classic CAVE is a cube-shaped VR room, typically 3m x 3m x 3m, with completely computer-projected screens on the walls, floor and sometimes ceiling. All participants wear active stereo glasses to see and interact with complex 3D objects [31].
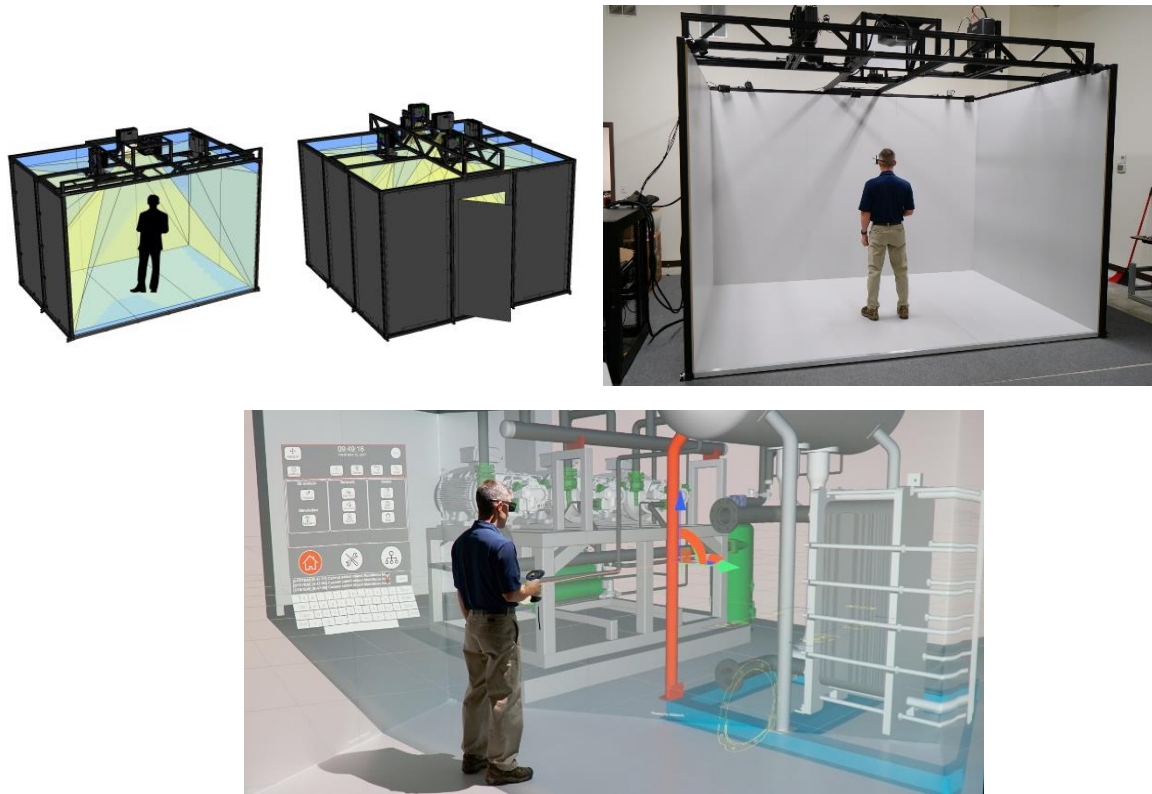
Figure 5. *VisCube™ M4 CAVE system [140]*

2.4. Virtual Reality in Product Design

According to the taxonomy proposed by Muhanna [7], shown in Figure 3, VR systems are classified into three levels according to the degree of immersion. The so-called basic VR systems are the systems with the lowest degree of immersion. VR systems with a higher degree of immersion than the base class are experienced in the class defined as partial immersion VR systems. Finally, the full immersion VR systems have the highest level of immersion.

Some scientists underlined the versatility of VR in terms of different design functions and emphasized the importance of applying VR systems at every stage of the process by using the right software and VR devices at the appropriate design stage [32, 33]. Others are more focused on using VR for specific applications. For example; Cecil and Kanchanapiboon [34], and Camburn et al. [35] highlighted the importance of using VR in the early design stages, where design issues can be better identified through VR, resulting in improved product quality and reduced development time and cost.

Stark et al. [36] and Falcão and Soares [37] emphasized the usefulness of VR systems in product evaluations related to human interaction. Zignego and Gemelli [38] have argued that VR is useful for simulations, although they are skeptical of the product's potential for aesthetic evaluation.

In some of the analyzed papers, the scientists also evaluated the degree of immersion and its use with additional technologies and tools to provide realistic presence in the virtual design environment. For instance; Stark et al. [36] argued that VR is mature enough to activate users' sensory immersion and provides an increasingly realistic interaction and experience with a virtual prototype. On the other hand, other scientists considered this technology only as a complementary tool because they reported that VR should be integrated with physical objects and haptic systems to give an acceptable sense of immersion [35, 39, 40]. Since the sense of touch is an important consideration especially when considering the virtual environment, using a real object as haptic feedback can enable full manipulation control in the immersive virtual environment [41].

Rebelo et al. [42] examined VR devices and their corresponding degrees of immersion, but limited their work to user-centered design when they analyzed how VR systems could be used in design. Jimeno and Puerta [43] studied VR only with CAD and Computer Aided Manufacturing technologies to understand the importance, benefits and developments of VR. Similarly, Berg and Vance [44] turned their attention to decision-making processes to strengthen innovation using VR. Kovar et al. [45] expanded his research area to other design processes, but his work was limited in connection with VR's contribution to Industry 4.0.

Many scientists have focused on only one phase or one particular aspect of the design process. While some emphasized that VR had a higher impact in the early design stages [34], others argued that this technology was better used in product evaluation due to its immersive capabilities [37].

In 2003, Schnabel and Kvan [46] showed that students working in two dimensions can accurately reconstruct interconnected forms, but still do not fully understand three-dimensional arrangement (p.442). According to the study, students who used VR to evaluate arrangement had a much better understanding of spatial relationships.

In 2014, Abdelhameed noted a link between the creativity of some students and the perception provided in the use of VR. This study also strengthened Schnabel and Kvan's conclusions about users' awareness of spaces. It was concluded that the strongest effect of VR was on form propositions, form compositions and form discovery [47].

According to the functions supported by VR technologies in product design, Berni and Borgianni [4] identified six macro categories: early stages, co-design, 3D modeling, virtual assembly and prototyping, mechanical simulation, finite element method (FEM), product evaluation and education purposes. The articles published between 1997 and 2020 according to the categories and VR technologies used are given in Table 1.

Table 1. *Distribution of articles published between 1997 and 2021 by VR technologies and categories*

	VR technologies used			
Categories	HMD	Desktop	CAVE	Unspecified
Early stages	Yang and Lee [48]. Evans, Hoover and Winer [49]. Velasquez [50].	Fiorentino et al. [51] Ye et al. [52] Keefe et al. [53]	Mäkelä et al. [54] Krause et al. [55] Israel et al. [56] Israel et al. [57] Eroglu et al. [58]	Lau [59] De Araùjo [60] De Araùjo [61] Song et al. [62]
Co-design	Bordegoni et al. [63]	Wickman and Söderberg [64] Choi and Cheung [65]	Lehner and DeFanti [66] Bochenek and Ragusa [67] Zhang et al. [68]	Pappas et al. [69] Makris et al. [70]

				Choi and Cheung [65] Noon et al. [71] Berg and Vance [72] de Back et al. [73]	
3D modeling	Butterworth et al. [74] Kraal and Vance [75] Huang and Lee [76] Huang, Lin and Cai [77]	Kameyama [78] Dani and Gadh [79] Kraal and Vance [75]	Krause et al. [80] Noon et al. [71] Toma et al. [81]	Achten et al. [82] Yan et al. [83] Chen et al. [84] De Araùjo [85] De Araùjo [86] Freeman et al. [87]	
Virtual assembly and prototyping, mechanical simulation, finite element method (FEM)	Jayaram et al. [88] Yeh and Vance [89] Jayaram et al. [90] de Sa and Zachmann [91] Moreau et al. [92] Schilling et al. [93] Sung et al. [94] Jayasekera and Xu [95] Wolfartsberger [96] Lukaˇceviˊc et al. [97]	Wickman and Söderberg [98] Choi and Chan [99] Choi and Chan [100]	Lehner and DeFanti [66] Ryken and Vance [101] Abulrub et al. [102] Toma et al. [81] Berg and Vance [72] Guo et al. [103] Guo et al. [104]	Pappas et al. [105] Raposo et al. [106] Bruno et al. [107] Wang ve Dumont [108] Makris et al. [109]	
Product evaluation	Evans et al. [110] Söderman [111] Bordegoni et al. [112] Park et al. [113] Rentzos et al. [114] Marks et al. [115]	Ye et al. [52] Park et al. [113]	Söderman [111] Bordegoni and Ferrise [116] Rojas et al. [117]	Tideman et al. [118] Van Der Voort and Tideman [119] Lanzotti et al. [120] Backhaus et al. [121] Zhang et al. [122]	

	Górski et al. [123] Valencia-Romero [124] Elbert et al. [125] Riegler et al. [126] De Crescenzio et al. [127] Wingler et al. [128]			Violante et al. [129] Liu et al. [130]
Education	Bharathi and Tucker [131] Obeid and Demirkan [132]	Impelluso and Metoyer-Guidry [133] Bharathi and Tucker [131]	Abulrub et al. [102] Bordegoni and Ferrise [116]	Achten et al. [82] Abulrub et al. [102] Backhaus et al. [121]

The number of articles published between 1997 and 2021 according to the categories and technologies used in Table 1 is shown in Figure 6. Accordingly, the highest number of articles is in the product evaluation category, where head-mounted VR technologies are used, and the least number of articles is in the co-design category, where head-mounted VR technologies are used.

***Figure 6.** Number of articles published between 1997 and 2021 by the technology used and categories*

2.4. VR modeling and Design Applications

Oculus Medium (Oculus VR, 2016): VR sculpting tool with the most advanced toolset and fully focused on the creation of VR objects (Figure 7). The program, in which Oculus Rift and Oculus Touch controllers are used, attracts the attention of character developers for the game industry. Oculus VR, the VR glasses company, is currently operated by Facebook [134].

Figure 7. Spock model created with Oculus Medium [141]

Tilt Brush (Google, 2016): VR platform developed by Google for creating 3D artistic models with a sketch look. It offers users an immersive experience in the third dimension, allowing them to see and experience the work from all possible angles [134]. The program supports working with surface-oriented objects in areas such as fashion and industrial design (Figure 8).
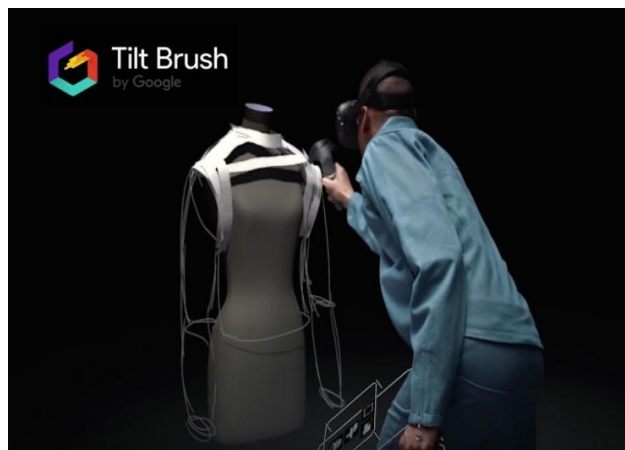

Figure 8. Use of Tilt Brush in fashion design [142]

Fuzor (Kalloc Studios, 2016)/ Enscape (Enscape 3D, 2016): Fuzor and Enscape are Revit plug-ins that transfer Revit models to an VR-simulated environment for users to experience. It is mostly used for limited design tasks such as visualization and changing materials [135].

Rhino SG (Minddesk VR, 2017): Rhino VR is a Rhinoceros 3D add-on that allows VR controller to act like a 3D mouse. Primitive shapes are created in the hand position and the application, which has a limited function as a full-scale architectural design tool, is under development [135].

Gravity Sketch (Paredes Fuentes, D. S., Oluwaseyi, 2017): Gravity Sketch is an intuitive 3D design platform for interdisciplinary teams to create, collaborate and revise in a completely new way. The user can express their ideas in real time at any scale from concept sketches to detailed 3D models, view and manage their designs on the desktop using the cloud platform, and integrate the end-to-end workflow into Gravity Sketch. The design toolset controlled by motion interaction as the primary input method provides an

intuitive experience [136]. As seen in Figure 9, the models created in the program can be exported and further developed on other software platforms.
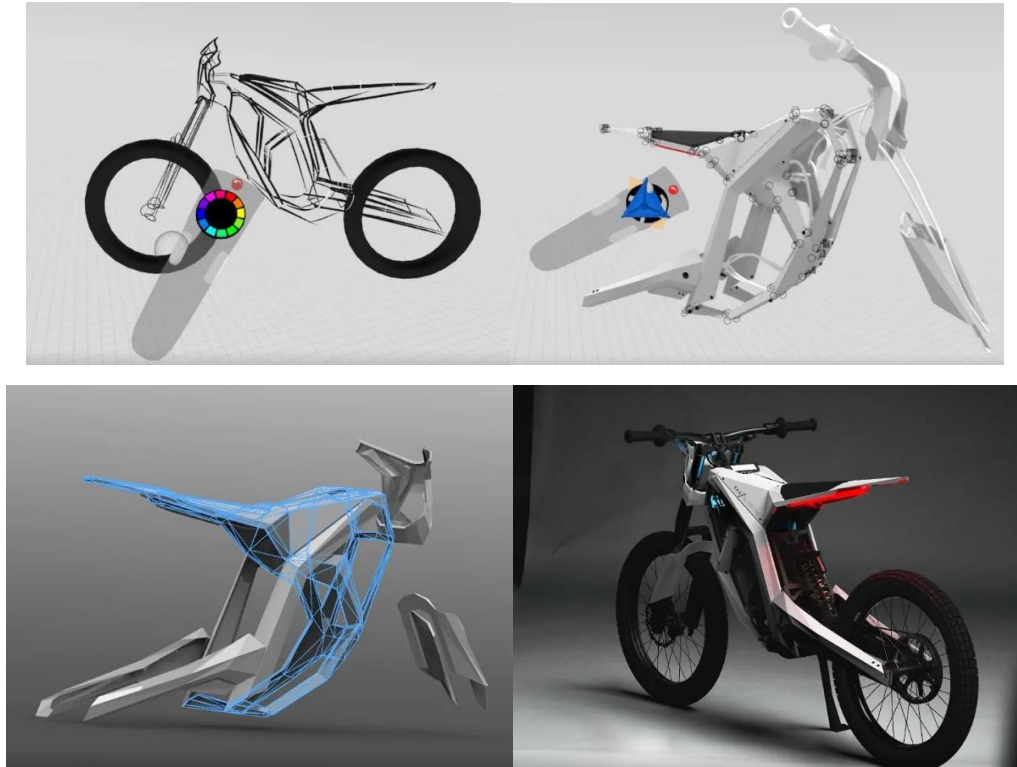
Figure 9. Motorcycle design by Alex Hodge using Gravity Sketch [143]

3. CONCLUSION

In this study, whose aim is to review the existing literature on VR technologies and the use of these technologies in the field of product design, to serve as a resource for future research and to give suggestions about the topics that should be focused on, the current literature is the definition, development, classification of VR, current VR applications, and VR in product design. Accordingly, as in many areas, with the rapid development of VR technologies, it is seen that the use of these applications in product design has started to become widespread. It can also be said that the researches on the use of these technologies in product design have increased from year to year. Six macro-categories (early stages, co-design, 3D modeling, virtual assembly and prototyping, mechanical simulation, finite element method (FEM), product evaluation and training) developed by Berni and Borgianni [4] of articles published between 1997 and 2021 and used. When we look at the distribution by technologies (HMD, desktop and CAVE), it is seen that the most articles are in the product evaluation category where head-mounted indicators are used, and the least number of articles are in the co-design category where head-mounted indicators are used. Under the category of head-mounted displays in the taxonomy developed by Muhanna [7] in recent years, wireless mobile head-mounted displays (such as Oculus Quest, HTC Vive Focus) and VR design and modeling applications (such as Gravity Sketch and Tilt Brush) has grown rapidly. Therefore, the use of VR technologies in product design has become more convenient, including in the early design phases. Looking at Table 1, it can be seen that the researches in 2020 are concentrated in the early stages category where head-mounted indicators are used.

This study covers all six macro-categories (early stages, co-design, 3D modeling, virtual assembly and prototyping, mechanical simulation, finite element method (FEM), product evaluation and training) developed by Berni and Borgianni [4] for the next researches using current technologies. It also shows that it can focus on categories that are open to development such as early stages and co-design, which are the subject of less research.

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