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HEAD-MOUNTED DISPLAY WEARABLE DEVICES ERGONOMICS AND USABILITY

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Abstract: *Wearable devices such as head-mounted displays (HMD), augmented reality glasses and mixed reality headsets have started to be widely adopted in various domains. These devices have been designed to support human activities using interactive digital content. There are various research studies regarding their implementation and frameworks used to select the suitable wearable devices in various domains, but their ergonomics, ease of software development and usability are not discussed in detail. Within this paper the authors have analyzed the most popular HMD devices available on the market that can integrate 3D content to answer four proposed research questions. The authors have analyzed the applications they developed during recent years in various domains such as engineering, teaching, industrial maintenance, and cultural heritage.*

Key words: *wearable technologies, ergonomics, virtual reality, augmented reality, mixed reality*

1. INTRODUCTION

Wearable devices have changed a lot over the last decades. The most important aspect is related to their overall size and weight, modern wearable devices are designed to be lightweight and integrate a wide variety of sensors and connectivity options. Wearable devices integrate various wireless technologies to facilitate data exchanging and user interaction.

As presented by Burmaoglu et al. [1], wearable technology comprises all devices that can be worn on a user`s body to provide various computing tasks for their daily activities. Wearable technology has emerged as one of the fastest-growing segments in the high-tech market, the highest number of patent applications are in the field of healthcare and medical devices.

Most wearable devices relate to the healthcare field, these are intended to gather real-time data which is then transferred towards other devices such as a smartphone for the user to better analyze them, some wearable devices such as smart watches/bracelets integrate digital displays to allow the user to visualize the data.

In healthcare field, advanced wearable devices that integrate detailed interactive 3D models are used mostly in teaching and training activities; the same principle applies to other industries such as industrial engineering, automotive industry, architecture, interior design, education, military, retail, entertainment, arts and design, cultural heritage.

Wearable devices capable of integrating 3D models have emerged as useful tools in the assessment of various tasks within controlled setups using custom designed applications.

As presented in [2], the popularity of wearable technology is set to increase exponentially within the near future. Their research study presented that IDTechEx consultancy company forecasted that wearable technology market will rise to a market of 74$ billion with over 3 billion wearable devices by 2025.

As presented by Tao Xiaoming in 2005, wearable technologies opened a door to many exciting applications which has led to another technological revolution like the internet and mobile communication industries [3]. This technological revolution integrates digital environments that make use of detailed 3D models.

The aim of this research paper is to analyze six of the most popular wearable devices that integrate 3D models regarding their ergonomics, ease of software development and usability. The research integrates virtual reality (VR), augmented reality (AR), and mixed reality (MR) wearable devices. These HMD wearable devices have one thing in common, they can integrate 3D models.

The research study explores the following research questions (RQ), to assess the ergonomics and usability of wearable devices that integrate interactive 3D models:

- Research Question 1 (RQ1): Are wearable devices ergonomic?
- Research Question 2 (RQ2): Are wearable devices designed to facilitate ease of development and usability?
- Research Question 3 (RQ3): Are wearable devices suited to be used in remote areas with limited connectivity?
- Research Question 4 (RQ4): Are wearable devices capable of meeting specific needs and requirements?

To investigate HMD wearable devices ergonomics and usability we have analyzed the wearable devices and the applications we developed and implemented in recent years in teaching activities, industry and in the field of digital cultural heritage.

2. RELATED WORKS

A recent systematic literature review of wearable devices ergonomics has been conducted by Stefana et al. [4]. Their systematic review of wearable devices made use of a three-step rigorous selection process that integrated 28 papers containing 24 studies. The researchers have managed to highlight the strength and weakness of different approaches and have also defined a framework of analysis that is useful for both researchers and practitioners. With a wide variety of wearable devices available on the market, the process of selecting the most suitable technology for ergonomic assessment in both industrial and non-industrial settings represents a challenging task [4].

The key ergonomics requirements for HMD wearable devices used in surgery are presented within a research article by D'Amato et. al within the European Horizon 2020 VOSTARS project [5]. They have managed to identify over 150 requirements of augmented reality headsets in the field of healthcare – surgery. The research project proposed a mechanical solution for a HMD wearable device with a tilted downward and upward visor and other customizable features.

An interesting, related work regarding the use of HMD wearable devices in industrial environments has been conducted by Ashley M. Toll. His Master`s Theses research study compared two common HMD (Microsoft HoloLens and RealWear HMT-1) used by coal power plant workers [6]. The workers performed five routine inspection tasks using coal burning equipment with and without the HMD wearables devices. Indicators such as eye strain and forces of the neck and shoulder muscles (electromyography muscle activity) were analyzed. The users had a decrease blink rate which is one of the main factors of eye strains and dry eye syndrome. Another significant finding was that workers felt a little more cautious about their situational awareness with the HMD than without them.

The acceptability of HMD and related human factors regarding to the adoption of AR/VR equipment in today`s Industry 4.0 environment has been studied by Lanyi et al. [7] Their findings revealed that the productivity of various activities related to industrial production can be increased by adopting these new technologies but at the same time they can provide distraction that can raise various safety issues if they are used directly in the production environment [7].

Other researchers have conducted ergonomic studies regarding the design of a workplace using virtual reality paired with a Motion Capture Suit. Their pilot case study has demonstrated that the combination of VR Technologies and MoCap suits allows an accurate ergonomic evaluation of an assembly workstation. The Mocap suits enables that all the working positions that a worker adopts to be analyzed with accurately, not just the hands of the user that are usually tracked by virtual reality equipment. The authors have proposed a further solution to use advance hand tracking technology that would capture the movement of their hands in real-time.

Related works regarding the use of mixed reality wearable devices (Microsoft HoloLens) are presented by Lang et. al within production and logistics operations. The limitations identified by the authors were mainly linked to the small projection surface and limited gesture controls available on the first generation of HoloLens from 2016 [8] that have been improved with the release of the second generation device.

3. MATERIALS AND METHODS

Within this section we present the HMD wearable devices that have been studied and compared to identify their ergonomics and usability. A total of six HMD wearable devices have been included within this comparative study and they represent some of the mostly commonly used HMD that are currently commercially available. The wearable devices include both virtual reality and augmented reality/mixed reality devices. We have chosen only VR Wearable devices that can enable Pass-through optics for this case study. Pass-through technique is a feature that allows the user to step outside the virtual environment and see the real-time view of his surroundings. Pass-through optic types implemented on VR/AR/MR wearable devices is based on the sensors of the headset to visualize what the user would see if he were able to look directly through the front of his headset into the real word around him.

For the Google Cardboard this represent a more challenging task that requires the use of the camera sensors while the other three virtual reality HMD integrate a predefined system that enable a low-resolution Pass-through visualization. As presented in the Table 1, the first four wearables' devices use Pass-through while the other two devices are wearable glass type devices and have a see-through optics visualization. The technical specification presented in Table 1 have been summarized to facilitate the comparison and analysis of the studied HMD wearable devices.

Table 1

The analyzed HMD wearable devices and their specifications.

	Google Cardboard	Meta Quest 2	HTC Cosmos	Valve Index	Epson Moverio BT40-s	Microsoft HoloLens 2
Wearable device category	Virtual Reality	Virtual Reality	Virtual Reality	Virtual Reality	Augmented Reality	Mixed Reality
Optics type	Pass-through	Pass-through	Pass-through	Pass-through	See-through	See-through
Display type	Depending on the smartphone	LCD	LCD	LCD	Si-OLED	LBS (Laser Beam Scanning)
Display resolution	Depending on the smartphone	1832x1920	2880 x 1600	2880 x 1600	1920 x 1080	1440 x 936
Weight	Depending on the smartphone	503g	645g	809g	95g	566g
OS	Depending on the smartphone	Android based	Windows, Linux and MacOS	Windows, Linux and MacOS	Android based	Windows Holographic
Wifi	Depending on the smartphone	6	Via PC/Laptop	Via PC/Laptop	5	5
Bluetooth	Depending on the smartphone	5.0	Via PC/Laptop	Via PC/Laptop	5.0	5.0
GPS	Depending on the smartphone	No	Via PC/Laptop	Via PC/Laptop	Yes	No
Battery operating duration	Depending on the smartphone	2-3 hours	Requires to be plugged in	Requires to be plugged in	1-2 hours	2-3 hours

3.1 Virtual reality wearable devices ergonomics

A virtual reality wearable device usually consists of multiple components, therefore their ergonomics are influenced by both the Head-Mount display as well as the controllers. The simplest portable VR wearable devices analyzed within this paper were initially built from fold-out cardboard (Google Cardboard) or made from plastic (Figure 1). These were mostly used as smartphone holders with straps to position the smartphone display in from of the user`s eye.

These devices make use of the smartphone processing capabilities to process the virtual reality environment and the interactions were done mostly using a Bluetooth controller.

Unfortunately, these two virtual reality HMD wearable devices have limited adjustments therefore offered poor ergonomics and don’t fit very well on the user`s head. These are also compatible only with smaller and thin smartphones that usually don’t integrate the best technical specification both in terms of processing capabilities, display resolution and good camera sensors.

The second analyzed virtual reality wearable device is the most commonly available all-in-one VR equipment the Oculus Quest 2. Recently the headset has been rebranded as Meta Quest 2 (Figure 2) with the parent company Facebook rebranding to facilitate the company new focus on virtual reality and metaverse.

Fig. 1. Google Cardboard VR Headset and a similar plastic case VR Headset [9]

Fig. 2. Meta Quest 2 VR Headset and the head strap replacement to enable the HMD to be flipped up [10]

Fig. 3. HTC Cosmos VR Headset with built in flipping visor and adjustable headphones [11]

The ergonomics of this headset are far superior to the previously presented virtual reality HMD wearable devices. The only drawback of the original designed of the Oculus Quest 2 is that the visor was fixed. The headset can be upgraded with custom design that allow the headset to be flipped up, allowing the users to check his surrounding without taking off the head strap.

As presented in Table 1, Meta Quest 2 is a lightweight virtual reality and is not using tethering technologies which require additional devices and a PC or a laptop to process the virtual reality environment. This is currently the most popular portable HMD wearable device currently available on the market and has an Android based operating system.

The third wearable device analyzed is the HTC Cosmos virtual reality system (Figure 3). This system requires either a laptop or a workstation to process the virtual reality environment but doesn’t require additional tracking sensors, therefore the solution represents a viable portable solution.

This HDM virtual reality wearable device includes adjustable headphones and a flipping visor by default, the headset was released on the market in 2019. The main advantage over Meta Quest 2 is mostly in terms of processing capabilities, but at the same time this can also be considered as a disadvantage considering that the headset needs to be connected to a PC or a laptop to be used. The headset has a wireless adaptor that can be mounted but from our experience the wireless adaptor adds a slightly noticeable delay within the virtual environment and requires additional hardware components.

The next virtual reality wearable devices analyze within the research study is represented by the Valve Index. This is an advanced HMD virtual reality wearable device that needs to be used in pair with a PC or a laptop. It provides better tracking then HTC Cosmos or Meta Quest 2, but it also requires at least 2 tracking sensors (base stations) to be used to define the tracking area which makes the overall solution less portable (Figure 4) as the two sensors should be elevated at around 2 m and as presented in the figure below to facilitate accurate tracking.

In terms of ergonomics of both the HDM as well as the controllers offer a wide variety of adjustment so that each user can find the perfect comfortable position of the HMD on their head as well as adjustable controllers that fit various hand sizes and which integrate built-in force sensors that can be used to grab objects within the virtual by squeezing the controllers.

3.2 Augmented reality wearable devices / Mixed reality wearable devices

The fifth analyzed wearable device is the BT40-S augmented reality (AR) glasses equipped with a touchscreen controller. This wearable device is powered by the popular Android OS and represents the most lightweight HMD wearable device out of all the analyzed devices (Figure 5).

The glasses ergonomics are not great as they have thick frames and a small projected screen, but the main drawback of the solution is that the interaction is mostly done by the user using the touchscreen controller as the equipment only supports limited natural gesture interaction. The glasses are mostly intended for augmented reality application that are triggered by various markers analyzed by the device`s camera.

The last analyzed wearable devices from this study is the popular mixed reality Microsoft HoloLens 2 headset presented in Figure 6.

The Microsoft HoloLens 2 has great ergonomics as it has a good weight distribution and no cables. The battery is located at the back and the visor can be flipped up. The visor has an open design and enough room so that users with prescription glasses can use it without any problems.

4. DISCUSSIONS

To analyze the ergonomics, ease of development and usability of the six analyzed wearable devices we have addresses the research questions (RQ) presented within the paper introduction and research aim.

Fig. 4. Valve Index VR Headset presented at the top and the ideal room setup using two base station sensors presented at the bottom [11]

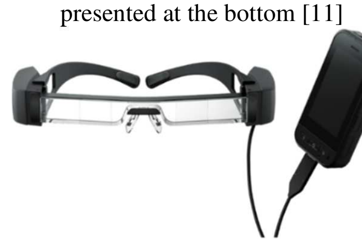

Fig. 5 Epson Moverio BT40-S AR wearable device [12]

Fig. 6 Microsoft HoloLens 2 wearable device [13]

The requirement related to ergonomics and human-device interactions were addressed by the following RQ:

Research Question 1 (RQ1): Are wearable devices ergonomic?

This is the most important aspects as ergonomics is essential to ensure safety by providing minimum discomfort and distraction for the users.

Google Cardboard and similar plastic phone holders that enable a smartphone to become a virtual reality head-mount display use Velcro strips headband and nose padding strip for the nose, but these designs offer limited adjustments therefore it doesn't fit the user head properly.

The Meta Quest 2 has improved adjustments, allowing the user to change the interocular distance, has a strap replacement that allows flipping visor and has good adjustable head straps. The Cosmos VR Headset has the same adjustments as the Meta Quest 2 the only ergonomic problem is related to the cable connection or the wireless adaptor that makes the HMD wearable device to be bulky, heavier and with the wireless extension an external battery bank wired to the headset.

The Valve Index Headset has great ergonomics but all those make the headset bulkier, and it doesn't have a flipping visor and requires external tracking sensors, but it has the most comfortable adjustable controllers.

The Epson Moverio BT40-S augmented reality glasses are lightweight, have good ergonomics but the thick glasses frame and narrow screen add up additional discomfort for longer period of use. The interaction supports some hand gestures, but they are mostly done using the touchscreen controller.

The HoloLens 2 mixed reality glasses have a good weight distribution, flipping visor and supports hand tracking. Their design is focused on functionality over looks and as presented before their design maintain enough eye relief so that people that wear prescription glasses can also wear the HoloLens 2 headset over the glasses. The HoloLens 2 are about 70% transmissive which means that external users can see the eyes of the users. For both the Epson Moverio BT40-S and Hololens 2 which are see-through optic wearable devices, usually users will feel more cautious about their situational awareness as the digital content is overlapped on to the real world.

Research Question 2 (RQ2): Are wearable devices designed to facilitate ease of development and usability?

To analyze the ease of development of the six head-mounted display wearable devices we have used the popular Unity cross-platform engine to develop and deploy custom applications.

The workflow to design applications intended for HMD wearable devices such as Google cardboard and other similar headsets that make use of a smartphone is effortless as Unity has built in support to deploy applications for smartphones. Even if the applications are easy to deploy for these HMD wearable devices their usability is very limited since these devices don't have the best interaction support.

Additional user interaction can be implemented but it requires additional hardware, the most common interaction makes use of a Bluetooth controller to allow the user to navigate the virtual scene. There are a wide variety of scripts available that greatly enhance Google`s official Cardboard SDK.

For the Meta Quest 2, the development process using Unity is easy as there are multiple assets available on the unity asset store. The most widely used asset is represented by the Oculus Integration package available for free. The only limitations regarding the usability of the applications are associated with the requirement of being connected to a Facebook account and being registered with an organization as presented in Figure 7.

To develop application for HTC Vive Cosmos and Valve Index HMD the following two free Unity Asset Stores presented in Figure 8 can be used. These packages offer a wide variety of customization and offers compatibility for other virtual reality devices.

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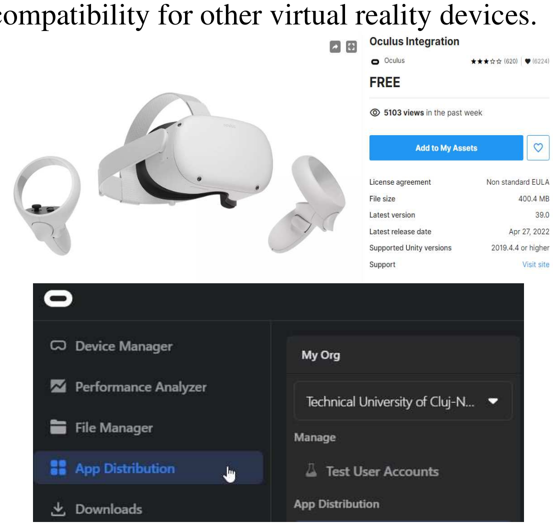

Fig. 7 Oculus Integration asset store package and the view of the Oculus Developer Hub – App distribution section [14]

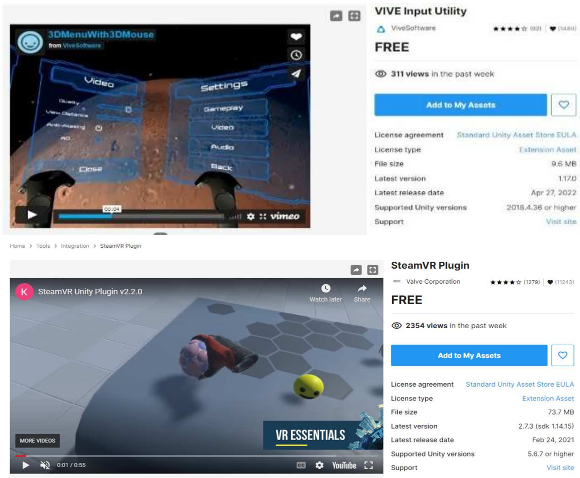

Fig. 8 Vive Input Utility [15] and SteamVR Plugin [16] available on Unity Asset Store

To develop application for Epson BT-40s the process is more complex as Epson doesn’t offer predefined Unity packages directly as it does for their BT-300 glasses. The development has to be done using MOVERIO SDK [12] which out of all analyzed SDKs is the hardest to work with and has the least features.

For Microsoft Hololens 2 the development in Unity is done using the MRTK-Unity (Mixed Reality Toolkit). The Mixed Reality Toolkit has a good documentation with multiple case study examples (Figure 9), but it requires multiple .NET individual components to be installed so that the *.APPX file can be compiled in Unity.

Microsoft HoloLens 2 uses Windows Holographic operating system, which is built around the API of Windows 10.

Research Question 3 (RQ3): Are wearable devices suited to be used in remote areas with limited connectivity?

From our findings based on the applications we developed, all HMD wearable devices are suitable to be used in remote areas, even if there is limited connectivity the applications should run properly as most of them are stand-alone builds that don’t require internet access. The only limitation is represented by the HTC Vive Cosmos and Valve Index, that require to be plugged in and connected to a PC or a Laptop. In remote area such as the high mountains of the Sarmizegetusa [17] Regia UNESCO World Heritage site, these devices require the use of external battery banks or in some cases even power generators.

Fig. 9 Mixed Reality Toolkit overview [13]

Fig. 10. Smartphone powered HMD virtual reality device and Epson AR glasses applications at the Sarmizegetusa Regia UNESCO World Heritage site

Figure 10 presents a case study of an HMD wearable device and a pair of Epson Moverio AR glasses used at the Sarmizegetusa Regia UNESCO World Heritage site to enable the visualization of 3D reconstructed Dacian temples.

For these remote areas, the use of smartphone-based devices such as GoogleCardBoard or similar plastic design can make use of the GPS of the smartphone to align 3D content directly over the existing in situ architectural monuments or standalone AR application intended for smartphones and tablets.

For industrial application that are implemented directly within the production environment, the use of augmented reality glasses could raise some problems since industrial environment usually have a low light environment. Only the AR glasses and Mixed Reality Headset are intended to be used directly in the production line. The virtual reality HMD wearable devices should all be used in predefined spaces within the factory layout, where the users can move freely without interfering with the production environment.

Most applications intended for the industry that integrate virtual reality wearable devices are intended for training activities, design, and production simulation while augmented reality and mixed reality applications are intended for production environment and on-site maintenance.

Even if HMD virtual reality headsets can enable Pass-through visualization of the real environment around the user, the current image quality of the Pass-through visualization can raise various safety concerns within the factory production areas and should only be used in safe environments with predefined cleared areas with no obstacles.

Research Question 4 (RQ4): Are wearable devices capable of meeting specific needs and requirements?

HMD wearable devices capable of using 3D content have reach the required technological maturity to be implemented with success in various domains and fields. The role of wearable devices in meetings the needs specific to service-oriented, customer-centric and demand-driven process within well-established industrial automation is presented within a case study research article [18].

Various HMD wearable devices have been integrated in other domains such as teaching and training where they have fulfilled the needs and requirements with ease and at affordable prices. One of the most important aspects regarding meeting the specific needs are related to the processing power of these devices. The HMD wearable devices that are not connected to a PC or a laptop and don't use tethering capabilities have limited capabilities regarding the development of realistic virtual reality environments. The same challenges apply to augmented reality and mixed reality glasses as complex applications that integrate high-definition 3D models and accurate physical collisions and interactions can rapidly generate performance issues on most devices.

As presented in Figure 11, adding a complex CAD model of an injection mold, the frame rate drops at around 18 fps when the user interacts with the 3D model.

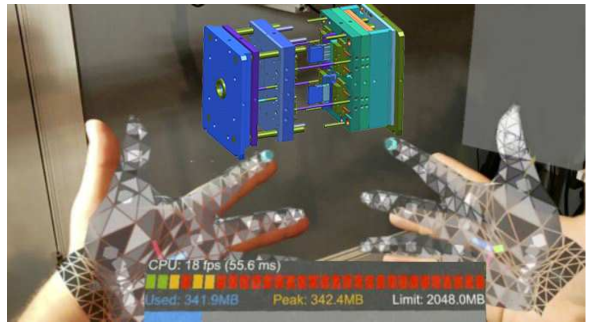

Fig. 11 Framerate drops and memory usage when dealing with 3D complex CAD models

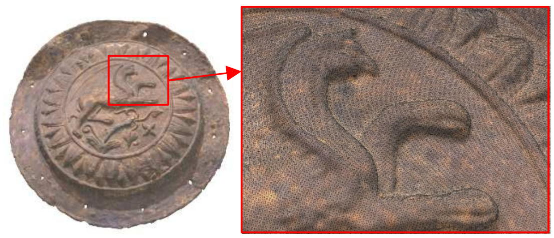

Fig. 12 High detail 3D scanned model of a Dacian ornamental shield

The 3D CAD models can be further optimized but this process requires additional processing, and it will lower the complexity of the final 3D model.

The same challenges are associated with the use of 3D scanned cultural heritage assets added to HoloLens 2, as 3D scanned models have a high number of vertices and polygons. An example is presented in Figure 12 with a 3D model of the gryphon Dacian ornamental shield from National Museum of Romanian History.

5. CONCLUSION

This paper presents a systematic overview of six of the most popular HMD wearable devices regarding their ergonomics, ease of development and utility. These HMD wearable devices have been used within engineering, teaching, training, and cultural heritage research areas.

Within the specific case studies, the HDM wearable devices have only been tested on a short period of time by each user of up to 10 minutes. As within this time frame each user was able to interact and follow the predefine use case scenario of each application.

It is recommended that users should not spend a high amount of time immersed within the virtual reality environment or have the augmented glasses/mixed reality glasses on for an extended period. From our case studies experience with the augmented reality glasses and since they are binocular with a screen for each eye, they cause some discomfort due to the fact that the screen overlaps over the real world.

As presented by other researchers the use of HMD wearable devices reduces the average blink rates. Considering that the mean normal spontaneous blink rate is between 12 and 15 blinks/ minute, the blink rates of users using HMD wearable devices highly decreases blink rates. The decreasing blink rate represents the main factor for eye strain and dry eye syndrome.

The strength and weakness of each HDM wearable devices has been presented both in terms of ergonomics but also regarding the ease of developing custom applications and their overall utility.

An important aspect is represented by the overall costs of the HMD wearable devices. We consider that Meta Quest 2 offers the best overall solution as it has multiple features at a very competitive price of around 300$. The applications are easy to develop and deploy using Unity. The only drawback is that developers must create a developer account and set up and Oculus developer organization. Another major advantage of Meta Quest 2 over the other virtual reality HMD is that the device has hand tracking capabilities with the built-in cameras. If Meta Quest 2 represents the most affordable solution, the Microsoft HoloLens 2 represents the most expensive solution. The starting price is around 3,500$ for the normal HoloLens 2 device, while the HoloLens 2 Industrial Edition costs 4,950$. The prices are even higher in other countries as it is available in only 29 countries as of May 2022 and only has a one-year warranty. The main difference is the ISO 14644-14 and designated ISO Class 5.0 and UL Class I, Division 2 certified. The HoloLens 2 is targeted mostly as a solution for industry, but the high price tag and its processing capabilities have a great impact of the usability of the HMD mixed reality solution.

Future research will be developed in the context of different university-industry collaborations due to the mutual advantages for education and research activities [19].

6. ACKNOWLEDGEMENT

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Dispozitive portabile montate pe cap - Aspecte ergonomice și de utilizare

Rezumat: Dispozitivele purtabile cu ecrane montate pe cap (HMD), ochelarii de realitate augmentată și căștile de realitate mixtă au început să fie adoptate pe scară largă în diferite domenii de activitate, pentru a susține derularea unor activități folosind conținut digital interactiv. Literatura de specialitate evidențiază cercetări diverse privind implementarea și cadrul de utilizare a acestor dispozitive, oferind argumente pentru selecția lor adecvată domeniul de utilizare, dar aspectele ergonomice relative la purtarea acestora sau ușurința de dezvoltare-utilizare a componentei software asociate lor nu au fost discutate detaliat. Astfel, articolul de față prezintă și analizează dispozitivele purtabile HMD cel mai frecvent folosite, disponibile pe piață și care pot integra conținut 3D pentru a răspunde celor patru întrebări de cercetare formulate. Mai mult, sunt analizate diferite aplicații asociate dispozitivelor HMD din diverse domenii precum inginerie, educație, întreținerea echipamentelor industriale și patrimoniu cultural.

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