engineering proceedings

MDPI

Proceeding Paper

CAVE Automatic Virtual Environment Technology: A Patent Analysis †

Fatma Beji [1], William de Paula Ferreira [1,*], Isabelle Pivotto Dabat [1] and Vitor Matias [2]

[1] Department of Systems Engineering, École de Technologie Supérieure, Montreal, QC H3C 1K3, Canada; fatma.beji.1@ens.etsmtl.ca (F.B.); isabelle.pivotto-dabat@etsmtl.ca (I.P.D.)
[2] Department of Specialized Education and Training, University of Quebec in Montreal (UQAM), Montreal, QC H2X 3R9, Canada; matias.vitor@uqam.ca
* Correspondence: william.ferreira@etsmtl.ca
† Presented at the 2024 IEEE 7th International Conference on Knowledge Innovation and Invention, Nagoya, Japan, 16–18 August 2024.

Abstract: Cave automatic virtual environment (CAVE) technology provides a highly immersive experience in virtual reality (VR) environments, transcending traditional boundaries of VR head-mounted devices. CAVE is applied to many fields, including education, construction, healthcare, and manufacturing. Despite its relevance, studies examining CAVE technology evolution and research directions are still lacking. To address this research gap, we analyzed patents using CAVE to understand the technology's development and identify opportunities for future research, development, and innovation. Patent data were collected from the Lens database and analyzed using data mining techniques. An increasing number of CAVE patents were granted, reflecting significant growth and investments in this field. The results highlight emerging trends in the development of CAVE systems, emphasizing various technical configurations and innovative applications across a wide range of fields.

Keywords: CAVE; patent analysis; data mining; virtual reality; immersive technologies

check for updates

Academic Editors: Teen-Hang Meen, Chun-Yen Chang and Cheng-Fu Yang

Published: 24 February 2025

Citation: Beji, F.; Ferreira, W.d.P.; Pivotto Dabat, I.; Matias, V. CAVE Automatic Virtual Environment Technology: A Patent Analysis. *Eng. Proc.* **2025**, *89*, 9. https://doi.org/10.3390/engproc2025089009

1. Introduction

A cave automatic virtual environment (CAVE) system consists of a cube-shaped virtual reality (VR) room with floor, ceiling, and walls as projection surfaces on which multiple projectors display images, creating an immersive 3D VR environment [1]. It represents an advance in VR, offering 3D immersion for users that transcends the traditional limits of the virtual experience provided by VR head-mounted devices [2,3]. The Electronic Visualization Laboratory first developed a VR CAVE system at the University of Illinois, in Chicago, in the early 1990s [4]. It has evolved significantly since then and has been used for different applications in various sectors such as education [5], medicine and healthcare [6–8], entertainment, leisure and culture [9], and manufacturing [10].

Despite CAVE's relevance, studies examining its technological evolution and research directions are still lacking. Accordingly, a patent analysis provides information on the competitive dynamics and innovations that characterize its evolution. It encompasses essential steps, such as technology exploration to identify new advances, technology landscape assessment to guide research and development, competitive analysis to position patents against competitors, and patent rankings to quantify their strength and identify new patent applications [11]. Even though patent analyses on augmented reality (AR) and VR have been conducted [12,13], there is a notable gap in the analyses of patents related to CAVE technology.

This study aims to fill this gap by applying an innovative data mining-based approach to quantitative analyses to understand patents associated with CAVE systems. The results provide information on the main CAVE technological developments, existing CAVE application domains, companies investing in and developing CAVE technology, and the classification of CAVE patents.

The remainder of this article is organized as follows: Section 2 provides a background review of CAVE systems. Section 3 introduces the research methodology. Section 4 presents the results, and Section 5 contains a discussion of the results. Lastly, Section 6 concludes this study.

2. Background

CAVE systems are classified into fully immersive versions, which plunge the user into a 360-degree virtual universe, and partially immersive versions, offering an immersive experience on a restricted selection of surfaces [1]. An example of a CAVE system is illustrated in Figure 1. The implementation of CAVE systems relies on direct or indirect projection techniques, allowing a virtual environment to be projected onto the walls of the dedicated space [8]. As described by Manjrekar et al. [4], a CAVE system includes six main components: (1) audio system; (2) video system; (3) cave calibration; (4) stereographic rendering; (5) tracking systems; and (6) graphic engine. The audio system enriches immersion with spatial sound environments, and the video system—which uses high-quality projectors—creates an illusion of depth by displaying stereoscopic images on walls and floors. Precise calibration of these systems is essential in aligning projections and tracking user movements perfectly. Stereoscopy offers two slightly different perspectives for each eye, and tracking systems adjust visual perspectives according to user movements, contributing to the immersive effect. Graphic engines—optimized for the high performance required by CAVEs—manage the rendering of virtual environments.

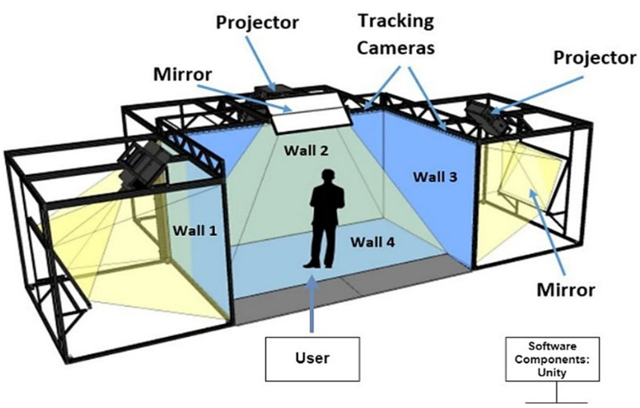

Figure 1. Illustration of a CAVE system [14].

For complete immersion, CAVE systems incorporate 360-degree cameras capable of capturing the entire surrounding space for a complete virtual reconstruction. For partially immersive configurations, 180-degree cameras are preferred, focusing immersion on specific areas of the environment [8,15,16]. Typically, four to eight cameras are used to ensure complete coverage and precise tracking of user movements. Projectors also play a key role in creating the illusion of a virtual world. Their number varies according to the configuration of the CAVE. A fully immersive system may require between four and six projectors to cover all the walls, floor, and sometimes the ceiling. Projectors must have high resolution to maintain superior image quality and can be distributed to avoid overlapping and unwanted shadows. Adopted projection technologies vary from digital light processing projectors to liquid-crystal display projectors, each with advantages in terms of brightness, contrast, and color fidelity [1]. The tracking system in a CAVE is essential for a successful immersive experience.

Various sensors are used in a CAVE, including optical, magnetic, and inertial motion sensors. These sensors detect user movements and adjust the virtual environment accordingly. The number of sensors required depends on the complexity of the tracking system and the desired precision. A standard configuration includes a dozen sensors strategically distributed throughout the space to capture all aspects of user movements. Necessary hardware includes high-resolution projectors, motion sensors, 3D glasses, and multidirectional audio systems, while the software includes rendering engines such as Unity or Unreal Engine, calibration software, and VR middleware such as VR Juggler or CAVElib, facilitating interaction between hardware and applications. The combination of these hardware and software components makes CAVE systems an exceptional platform for data mining and environmental simulations for different purposes.

3. Methodology

We adopt a quantitative-based patent analysis methodology for the identification of emerging technological trends, assessment of competitor activities, and detection of development and collaboration opportunities [11,17]. It also aids in mitigating risks of infringement and litigation by clarifying a technology's intellectual property [18]. Moreover, patent analyses are conducted to uncover unexplored research areas and guide research and development investments, ensuring a strategic alignment with market developments [19]. Furthermore, this methodology helps formulate strategies for protecting and capitalizing on inventions, thereby strengthening the innovative position of both academia and industry in the long term [17].

The Lens patent database was adopted as the main data source of the patents associated with CAVE technology, for specific reasons. First, Lens offers free access to a vast worldwide patent database, facilitating the exploration of a wide range of documents relevant to our analysis. Lens compiles data from various sources, including government patent offices in several jurisdictions and other international institutions. In addition, Lens offers a user-friendly and intuitive search interface and advanced data visualization features that facilitate patent analysis.

Table 1 presents the search protocol in this study. We identified 264 patents, from which 215 were selected for analysis, excluding redundant patents filed in different jurisdictions. After reviewing each patent, abstract, and claim, we excluded 73 patents that were beyond the scope of this research. These included patents involving water caves, wine cellars, plant containers called caves, or medical devices used in CAVE environments. The review results included 142 patents for further analysis using descriptive statistics and data mining (e.g., clustering techniques) based on the Python programming language and its specialized libraries (e.g., Pandas, Matplotlib, Seaborn, Scikit-learn).

Table 1. Search protocol.

Data source:	Lens
Search string:	(CAVE AND immersive) OR (CAVE AND virtual)
Period:	From 1992 (emergence of the 1st CAVE) to 7 June 2024
Search fields:	Title, abstract, and claims
Language:	English
Document:	Patents

4. Results

Of the patents included in the sample, 39.4% are active patents; 32.4% are patents pending evaluation, which means that they are still under examination by the patent office and have yet to be granted; 19.7% are patents interrupted or abandoned by their applicants before being granted or rejected; 5.6% are inactive patents, indicating that they are not commercially launched or awaiting renewal of their rights. Finally, 2.6% are expired patents, meaning that their legal validity period has ended and they are no longer protected. All these non-active patents were included in the analysis since they provide information on the development of CAVE technology.

Figure 2 shows the evolution of CAVE patents over time. From the first filings observed in the early 1990s corresponding to the creation of the first CAVE, a gradual increase in patent publications is observed until the early 2000s. From then on, a marked acceleration is visible, with a notable peak in 2022 showing 21 patents, which suggests an increased interest in CAVE technology due to key technological advances, the emergence of new application markets, or wider recognition of the immersive technology's commercial potential, and applications. Moreover, patent citations indicate a technology not recognized as essential by the community but that continues to impact current innovation.

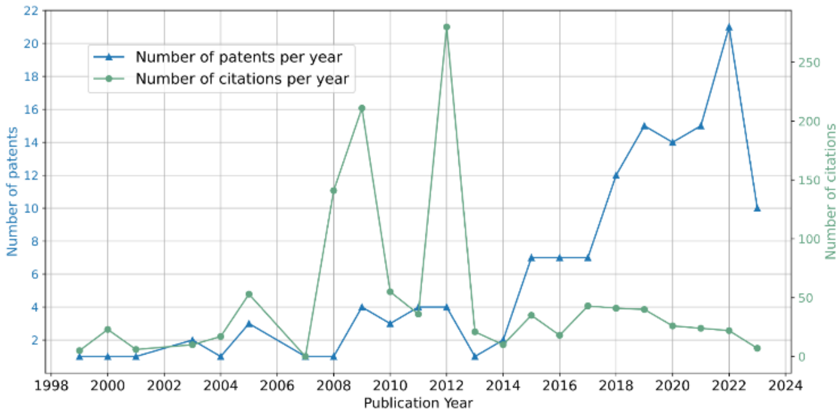

Figure 2. Number of patents and citations for CAVE.

The geographical distribution of patents relating to CAVE technology highlights the global scope of innovation and the variety of players involved. Figure 3 shows that China and the USA largely dominate the field with 54% and 24% of patents, respectively. Other countries including the UK and Japan have 1–3 patents, indicating a global interest and investment in this technology.

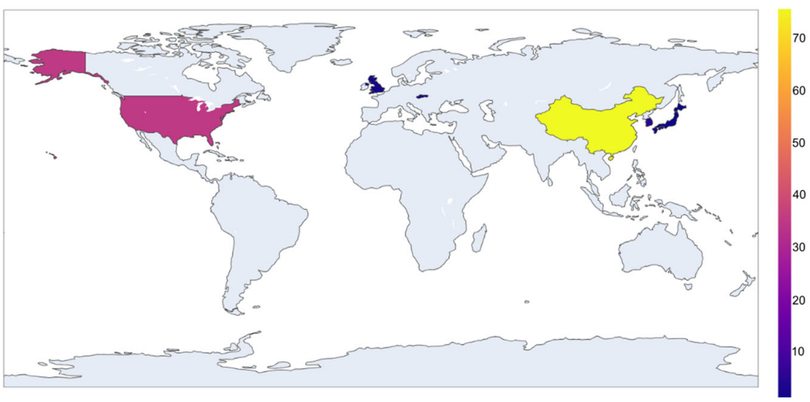

Figure 3. Geographical distribution by affiliation of authors.

Figure 4 shows the main patent applicants on CAVE systems. Well-known companies in the aeronautics and manufacturing sectors—such as Lockheed Corporation based in Bethesda, Maryland, United States with four patents, and Geely Holding Group, headquartered in Hangzhou, Zhejiang, China, with five patents—are among the leading applicants. Other entities—such as Hangzhou Yiyuqianxiang Technology, also located in Hangzhou, Zhejiang, China, and 3Di LLC, based in Unites States, —have three patents each. Industries and universities are contributing to the development of CAVE technology. For example, Jinan University, located in Guangzhou, Guangdong, China, has filed three patents, demonstrating academia's involvement in advancing this field.

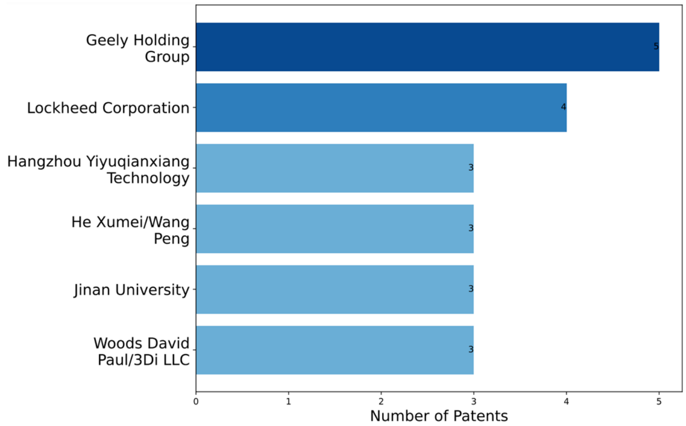

Figure 4. CAVE patent applicants.

Figure 5 summarizes the CAVE patent application domains. It indicates that the two leading areas are VR technology (audio and video equipment manufacturing), with 88 patents, followed by the manufacturing industry, with 16 patents. The gaming industry is also making considerable strides in innovation, with eight patents. This is closely followed by research and development in biotechnology and the medical and healthcare industries, as well as the automotive industry, each with seven patents. Other notable domains include education, human–machine interface (HMI), mining engineering, theater, video processing, photography, marketing consulting, and geosynchronization. The diverse range of domains illustrates the widespread applicability of CAVE systems.

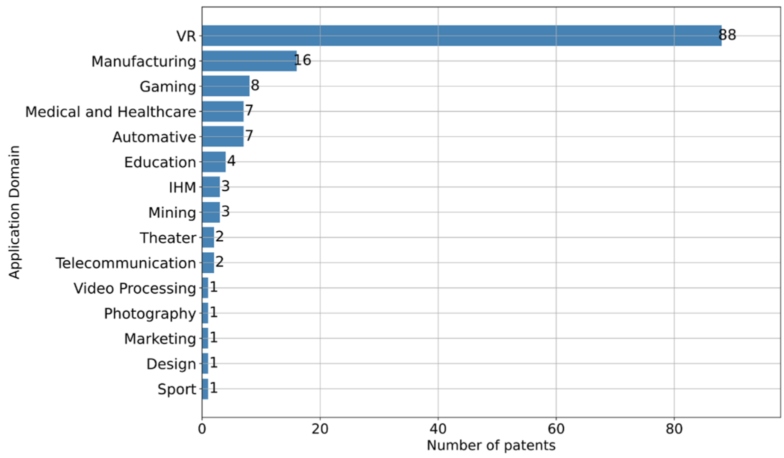

Figure 5. Patent application domains.

Two systems are used to classify patents according to their technical fields: cooperative patent classification (CPC) and international patent classification (IPC). CPC is a relatively recent system developed jointly by the European Patent Office (EPO) and the United States

Patent and Trademark Office (USPTO) and is designed to be more detailed and progressive than the reformed version of IPC. CPC is updated more frequently to reflect the rapid evolution of technology and innovation. Figure 6 shows the number of patents classified under different subcategories of CPC to identify the main innovations in CAVE systems. For example, physics-related sub-classes such as image-processing systems or head-tracking devices are predominant. This corresponds to the key aspects of CAVE technology, which relies on user interaction and complex image processing to create immersive environments.

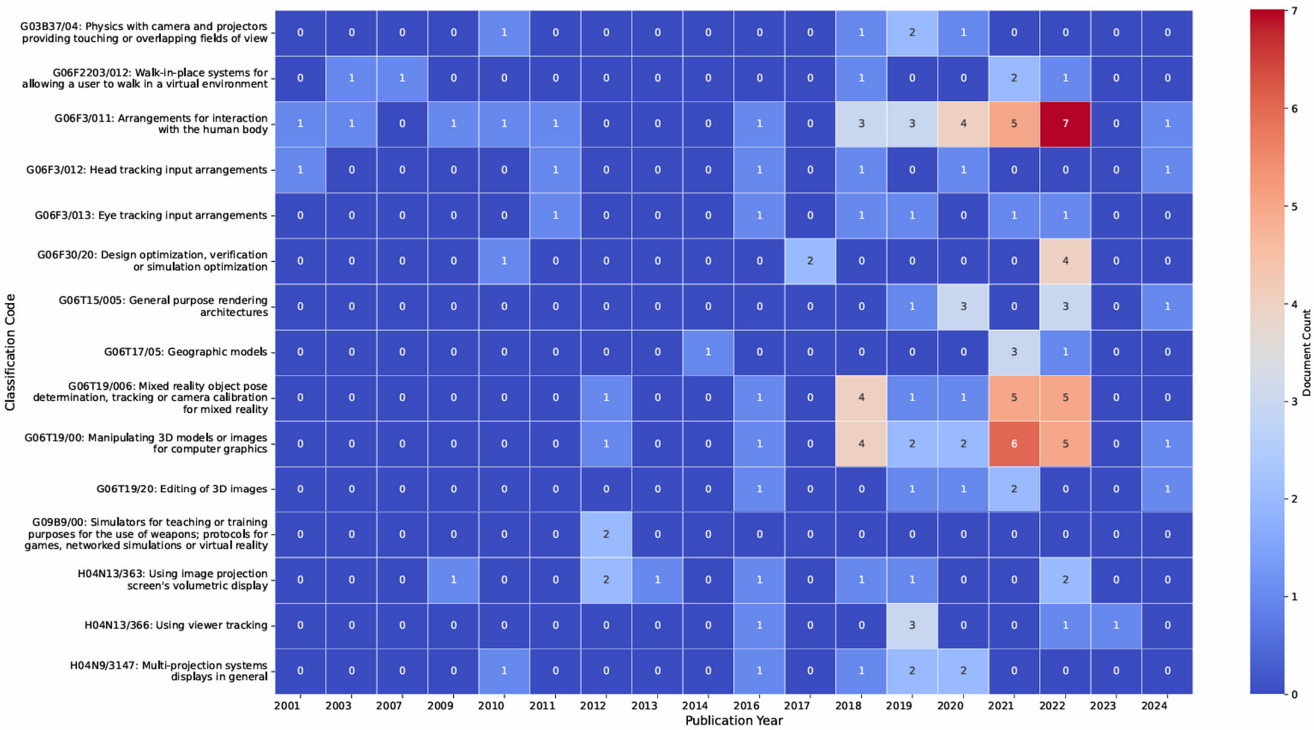

Figure 6. Evolution of patents on CAVE based on CPC.

Figure 7 presents a cluster analysis based on the classification of Manjrekar et al. [4], which describes a CAVE system in terms of its different components. The audio and video systems cluster (36 patents) includes technologies related to both audio and visual components essential for creating an immersive CAVE experience with advancements in sound systems, speakers, display screens, projectors, and integration methods. The CAVE calibration cluster (22 patents) focuses on the technical aspects necessary to ensure the accuracy and reliability of immersive environments, encompassing hardware and software crucial to precision calibration. The stereographic rendering cluster (21 patents) is dedicated to technologies that enable the creation of three-dimensional visuals, providing depth perception and enhancing virtual environment realism through stereoscopic display methods. The tracking systems cluster (34 patents) includes technologies tracking eye, hand, and body movements essential for natural and intuitive interactions within virtual environments to enhance the user experience through precise tracking capabilities. Finally, the graphic engine cluster (35 patents) includes software and hardware components responsible for rendering and managing graphics in a CAVE system, covering innovations in GPUs, rendering algorithms, and software platforms that support high-performance graphics rendering. Furthermore, we identified the CAVE clusters (four patents) to determine an entire CAVE variant, including portable or low-cost systems. It is important to note that some patents may fall into multiple clusters.

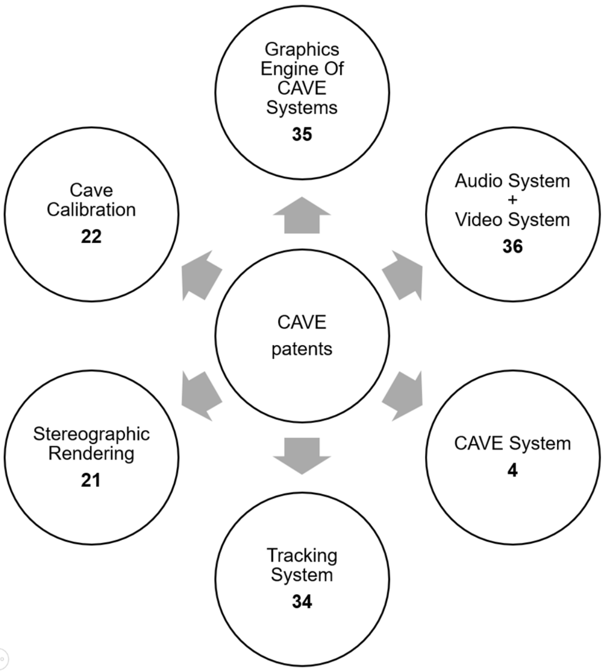

Figure 7. Cluster analysis.

5. Discussion

5.1. CAVE Technological Developments

The cluster analysis results show three major technological development areas: audio/video systems, graphic engines, and motion-tracking systems. Audio and video systems are crucial for creating an immersive experience in a CAVE environment. This includes projection technologies [20], high-resolution displays [21], spatial audio systems [20], and audio/video synchronization technologies [22]. These systems enable the simulation of realistic and immersive virtual environments, essential for a wide range of applications such as immersive training. Graphic engines are at the core of CAVE systems, enabling real-time generation of 3D images. They include advanced rendering algorithms, illumination techniques, and optimizations for handling massive data volumes. These engines ensure a smooth and realistic experience, essential for complex simulations and interactive environments. Motion-tracking systems capture user movements within the CAVE environment. They include camera-based motion capture, inertial sensors, and optical localization systems [23]. Precise motion tracking is essential for natural and intuitive interaction with virtual environments, thus enhancing user engagement and efficiency.

CPC also highlights the CAVE system's technological development aspects, suggesting two major development areas: human-body interaction devices and determining the pose of mixed-reality objects, tracking, or cameras. These devices include human–machine interfaces such as haptic gloves, force-feedback vests, and gesture recognition systems. These technologies enable more natural and immersive interaction with CAVE environments, increasing their utility in various applications such as medical training and manufacturing. Pose determination technologies for mixed-reality objects allow tracking of the spatial position and orientation of objects. They include AR and motion-tracking cameras, merging virtual and real worlds, and enhancing CAVE system capabilities for mixed- and augmented-reality applications.

In summary, the main technological developments in CAVE technology focus on improving immersion and interactivity in virtual environments. Advanced audio/video systems and graphic engines play a crucial role in creating immersive experiences. Motion-tracking systems and human-body interaction devices allow natural and intuitive interaction, which is essential for user engagement. Moreover, mixed-reality technologies and 3D manipulations are critical for advanced applications in various fields, ranging from education to industrial simulations. Finally, different CAVE system configurations are being developed to make it more affordable and portable [24]. These advancements indicate a growing interest in creating functional CAVE systems with immersive rendering capabilities.

5.2. CAVE Application Domain

Six major sectors were analyzed including VR, manufacturing, medical and healthcare, automotive, and education. VR (audio and video equipment manufacturing) and the manufacturing industry are the two leading application areas, highlighting their significant role in enhancing immersive experiences. The gaming industry, particularly electronic video game manufacturing, also leverages CAVE technology, emphasizing its role in creating immersive and interactive gaming experiences. Other domains include HMI, mining, theater, video processing, photography, marketing, resynchronization, design, and sports. CAVE technology is widely used in research, development, and training in the medical and healthcare sectors. Such broad applications underscore the versatility of CAVE technology and its potential for innovation across numerous sectors.

5.3. Development of CAVE Technology

The companies developing CAVE technology are located in the United States and China. In China, the leading company is Geely Holding Group, an automotive group that has developed VR simulation tools for vehicle models since 2018, eventually proposing a new CAVE system in 2020 to meet their technological needs. This product development approach based on specific user needs known as user-centeredness is a key element of the increasingly popular concept of design thinking. The approach of this company has contributed to developing a CAVE system addressing its challenges in automotive design.

In the USA, the leading company is Lockheed Corporation, a manufacturer in the aerospace and defense sector. It focused on developing immersive environments for CAVE technology with user tracking and motion capture. Although the company has since abandoned the development of CAVE technology, its patents have been frequently cited, ranging from 15 to 187 citations. Companies with highly cited patents contribute significantly to technological progress in their specific fields [25]. These highly cited patents signal key innovations or major technological advances, emphasizing their importance for the companies themselves and the overall evolution of technology.

However, even though private companies file a large number of patents, 23 patents are held by academics for various applications, including the development of a portable CAVE. Most of these academics are also found in the United States and China.

5.4. Trends and Dynamics

The CPC classification and the CAVE components/system taxonomy can be used to better understand CAVE technology (Figure 7). Consequently, 22 variants of the initial system developed by Cruz et al. in 1992 [26] and 1993 [27] and many application domains for CAVE technology were found. Additionally, numerous patents target CAVE technological components, such as combined audio/video systems, graphic engines, motion-tracking systems, visual rendering, and calibration systems.

For technological innovation, we focused on under-explored clusters, such as systems that include portable or low-cost CAVE systems. CAVE technology is expensive in terms of initial costs and maintenance fees [8]. Examining patents in the less common technical domains based on CPC classifications is beneficial. This approach provides manufacturers and companies with valuable information on the less-developed components of CAVE technology. Companies need to strategize their research and development efforts more effectively by identifying gaps and emerging areas within the patent portfolios. For instance, patents related to portable and cost-effective CAVE systems could address the current limitations and market needs [8].

Patent analysis helps in identifying technological gaps and understanding the competitive dynamics. Highly cited patents, such as those of Lockheed Corp., often indicate significant technological advancements and influence [25]. Companies can use this information to benchmark their innovations and identify key players and potential collaborators or competitors.

6. Conclusions

We analyzed the evolution and current state of CAVE technology through a patent analysis. The findings indicate a notable increase in granted CAVE patents since its inception in 1992, reflecting growing interest and advancements in the field. Moreover, a cluster analysis based on CPC provides information on the technological trends and competitive dynamics of CAVE technology. By focusing on under-explored areas, companies can drive innovation, reduce costs, and enhance the efficacy and accessibility of CAVE systems. The broad range of applications, from healthcare and education to industrial manufacturing and entertainment, demonstrates the versatility and impact of CAVE technology. The geographical distribution of patents and patent applicants reveals that the USA and China lead the patent filings on CAVE. While current innovations focus on enhancing immersive experiences and user interaction, future research is necessary to explore the development of more affordable and portable CAVE systems. As CAVE technology continues to evolve, it can revolutionize multiple sectors by providing immersive virtual environments to redefine user experience.

Author Contributions: Conceptualization, F.B., W.d.P.F. and I.P.D.; methodology, F.B., W.d.P.F. and I.P.D.; validation, F.B., W.d.P.F., I.P.D. and V.M.; formal analysis, F.B.; investigation, F.B.; resources, W.d.P.F., I.P.D. and V.M.; data curation, F.B.; writing—original draft preparation, F.B.; writing—review and editing, F.B., W.d.P.F., I.P.D., V.M.; visualization, F.B. and W.d.P.F.; supervision, W.d.P.F., I.P.D. and V.M.; funding acquisition, W.d.P.F., I.P.D. and V.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Ministère de l'Economie, de l'Innovation et de l'Energie (MEIE) of the Government of Quebec [N/Réf.: 2022-2026-PSOv2a-ETS-IS-63675].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Muhanna, M.A. Virtual reality and the cave: Taxonomy, interaction challenges and research directions. *J. King Saud Univ.-Comput. Inf. Sci.* **2015**, *27*, 344–361. [CrossRef]
2. Kageyama, A.; Tomiyama, A. Visualization framework for cave virtual reality systems. *Int. J. Model. Simul. Sci. Comput.* **2016**, *7*, 1643001. [CrossRef]
3. Flynn, C. An Open-Source Framework for Cave Automatic Virtual Environments. Ph.D. Thesis, Dublin City University, Dublin, Ireland, 2014.
4. Manjrekar, S.; Sandilya, S.; Bhosale, D.; Kanchi, S.; Pitkar, A.; Gondhalekar, M. Cave: An emerging immersive technology—A review. In Proceedings of the 2014 UKSim-AMSS 16th International Conference on Computer Modelling and Simulation, Cambridge, UK, 26–28 March 2014; pp. 131–136.

5. Freina, L.; Ott, M. A literature review on immersive virtual reality in education: State of the art and perspectives. In Proceedings of the International Scientific Conference Elearning and Software for Education, Bucharest, Romania, 23–24 April 2015; Volume 1, pp. 10–1007.
6. Wiebe, A.; Kannen, K.; Selaskowski, B.; Mehren, A.; Thöne, A.K.; Pramme, L.; Blumenthal, N.; Li, M.; Asché, L.; Jonas, S.; et al. Virtual reality in the diagnostic and therapy for mental disorders: A systematic review. *Clin. Psychol. Rev.* **2022**, *98*, 102213. [CrossRef] [PubMed]
7. Gromer, D.; Madeira, O.; Gast, P.; Nehfischer, M.; Jost, M.; Müller, M.; Mühlberger, A.; Pauli, P. Height simulation in a virtual reality cave system: Validity of fear responses and effects of an immersion manipulation. *Front. Hum. Neurosci.* **2018**, *12*, 372. [CrossRef] [PubMed]
8. Pivotto, I.D.; Matias, V.; de Paula Ferreira, W. Cave automatic virtual environment technology to enhance social participation of autistic people: A classification and literature review. *Res. Autism Spectr. Disord.* **2024**, *117*, 102453. [CrossRef]
9. Ishii, A.; Tsuruta, M.; Suzuki, I.; Nakamae, S.; Suzuki, J.; Ochiai, Y. Let your world open: Cave-based visualization methods of public virtual reality towards a shareable vr experience. In Proceedings of the 10th Augmented Human International Conference 2019, Ser. AH2019, Reims, France, 11–12 March 2019; Association for Computing Machinery: New York, NY, USA, 2019; pp. 1–8.
10. Yang, X.; Malak, R.C.; Lauer, C.; Weidig, C.; Hagen, H.; Hamann, B.; Aurich, J.C.; Kreylos, O. Manufacturing system design with virtual factory tools. *Int. J. Comput. Integr. Manuf.* **2015**, *28*, 25–40. [CrossRef]
11. Shalaby, W.; Zadrozny, W. Patent retrieval: A literature review. *Knowl. Inf. Syst.* **2019**, *61*, 631–660. [CrossRef]
12. Taotao, S.; Yun, L. Development of virtual reality technology research via patents data mining. In *Proceedings of the 2009 3rd International Conference on Teaching and Computational Science (WTCS 2009) Volume 2: Education, Psychology and Computer Science; Advanced Technology in Teaching*; Springer: Berlin/Heidelberg, Germany, 2012; pp. 111–116.
13. Evangelista, A.; Ardito, L.; Boccaccio, A.; Fiorentino, M.; Petruzzelli, A.M.; Uva, A.E. Unveiling the technological trends of augmented reality: A patent analysis. *Comput. Ind.* **2020**, *118*, 103221. [CrossRef]
14. Visbox, Inc. V isCubeT M C4-4K (Legacy). 2020. Available online: https://www.visbox.com/products/cave/viscube-c4-4k/ (accessed on 7 June 2024).
15. de Paula Ferreira, W.; Armellini, F.; de Santa-Eulalia, L.A.; Rebolledo, C. Modelling and simulation in industry 4.0. In *Artificial Intelligence in Industry 4.0*; Springer: Cham, Switzerland, 2021; pp. 57–72.
16. de Paula Ferreira, W.; Armellini, F.; de Santa-Eulalia, L.A.; Thomasset-Laperrière, V. A framework for identifying and analysing industry 4.0 scenarios. *J. Manuf. Syst.* **2022**, *65*, 192–207. [CrossRef]
17. Míguez, J.L.; Porteiro, J.; Pérez-Orozco, R.; Patiño, D.; Gómez, M.Á. Biological systems for ccs: Patent review as a criterion for technological development. *Appl. Energy* **2020**, *257*, 114032. [CrossRef]
18. Abbas, A.; Zhang, L.; Khan, S.U. A literature review on the state-of-the-art in patent analysis. *World Pat. Inf.* **2014**, *37*, 3–13. [CrossRef]
19. Feng, L.; Li, Y.; Liu, Z.; Wang, J. Idea generation and new direction for exploitation technologies of coal-seam gas through recombinative innovation and patent analysis. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2928. [CrossRef] [PubMed]
20. Zhou, X.; Li, S. Immersive Virtual Display System and Display Method of Cave (Cave Automatic Virtual Environment). 10 December 2014. Available online: https://lens.org/199-805-588-984-464 (accessed on 7 June 2024).
21. Mayer, E.; Odaker, T.; Kolb, D.; Müller, S.; Kranzlmüller, D. Led cave-new dimensions for large-scale immersive installations. In Proceedings of the 2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), Orlando, FL, USA, 16–21 March 2024; pp. 515–519.
22. Zhang, C.; Hu, Y.; Lyu, Y.; Chen, D.; Liang, Y.; He, L.; Liu, S. Multi-Channel Cave Type Projection Method. 6 November 2020. Available online: https://lens.org/084-003-292-225-085 (accessed on 7 June 2024).
23. Tseng, C.H. System and Method for Immersive Cave Application. 1 November 2018. Available online: https://lens.org/089-823-476-843-553 (accessed on 7 June 2024).
24. Neira, C.C.; Reiners, D. Portable Cave Automatic Virtual Environment System. 10 September 2019. Available online: https://lens.org/085-457-751-703-377 (accessed on 7 June 2024).
25. Breitzman, A.F.; Mogee, M.E. The many applications of patent analysis. *J. Inf. Sci.* **2002**, *28*, 187–205. [CrossRef]
26. Cruz-Neira, C.; Sandin, D.J.; DeFanti, T.A.; Kenyon, R.V.; Hart, J.C. The CAVE: Audio visual experience automatic virtual environment. *Commun. ACM* **1992**, *35*, 64–72. [CrossRef]
27. Cruz-Neira, C.; Leigh, J.; Papka, M.; Barnes, C.; Cohen, S.M.; Das, S.; Engelmann, R.; Hudson, R.; Roy, T.; Siegel, L.; et al. Scientists in wonderland: A report on visualization applications in the CAVE virtual reality environment. In Proceedings of the 1993 IEEE Research Properties in Virtual Reality Symposium, San Jose, CA, USA, 25–26 October 1993; pp. 59–66.