

CAVE automatic virtual environment technology: A patent analysis

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Abstract— CAVE technology provides an immersive VR experience beyond traditional headsets. It has applications in fields such as education, construction, healthcare, and manufacturing. However, there is a lack of studies on its evolution and research directions. This article fills the gap by analyzing patents related to CAVE systems using data from the Lens database and data mining techniques. The study finds a growing number of CAVE patents and identifies emerging trends in technical configurations and innovative applications across various fields.

1. Introduction

A CAVE system is a VR room with projection surfaces on its walls, floor, and ceiling, creating an immersive 3D experience. Developed in 1990 by the Electronic Visualization Laboratory at the University of Illinois at Chicago, CAVE has evolved significantly. Despite its relevance, studies on CAVE's evolution and research directions are lacking. This study uses data mining to analyze CAVE patents, aiming to answer: **RQ#1**-What are the main CAVE technology developments? **RQ#2**-What are the main application domains and companies investing in CAVE? **RQ#3**-How can CAVE patents be classified?

2. Background

CAVE systems are classified into fully immersive (360-degree) and partially immersive versions, using direct or indirect projection techniques. A typical CAVE system includes components like audio and video systems, calibration, stereographic rendering, tracking systems, and graphics engines.

These systems rely on high-quality projectors, 360-degree cameras, and sensors to create and track immersive environments. Hardware includes projectors and sensors, while software includes rendering engines and VR middleware (Fig 1).

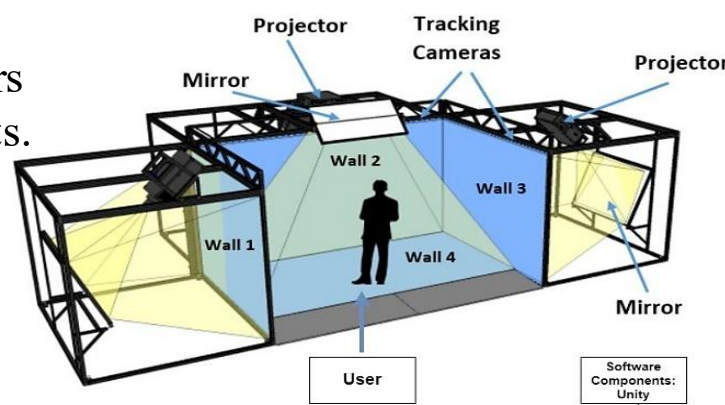


Figure 1. Illustration of a CAVE system. Source

3. Methodology

The Lens patent database was used to analyze CAVE technology patents from 1992 to June 2024

Table 1. Search Protocol

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

The initial search returned 264 patents, narrowed down to 142 relevant patents after excluding duplicates and unrelated entries. Of the patents in the sample, 39.4% are active, 32.4% are pending evaluation, 19.7% were abandoned before being granted or rejected, 5.6% are inactive, and 2.6% are expired. All patents, including non-active ones, were analyzed for insights into CAVE technology development.

Patent publications have gradually increased since the early 1990s, with a notable peak in 2022, indicating rising interest and technological advances (Fig 2).

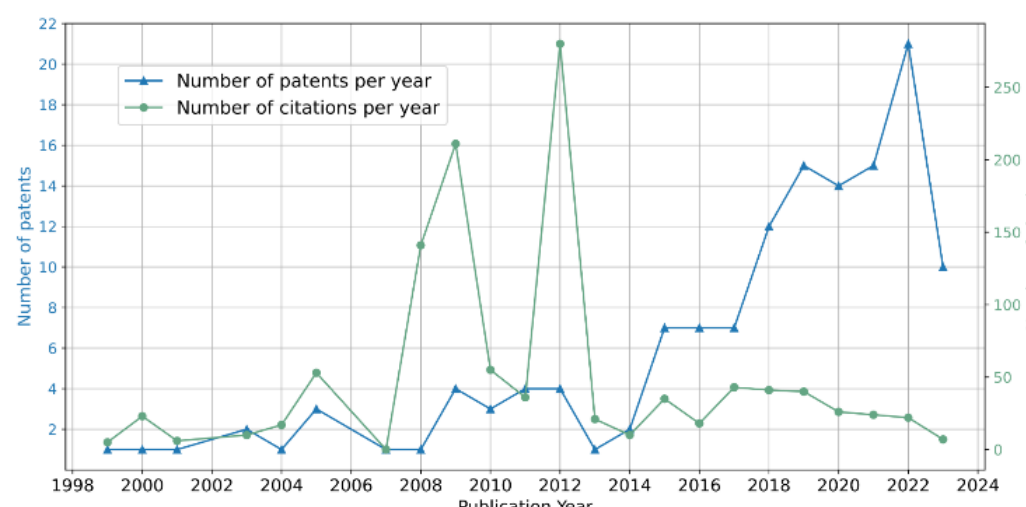


Figure 2. Number of patents and citations on CAVE overtime.

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4. Results

Geographically, China and the USA lead with 54% and 24% of patents, respectively, followed by the UK and Japan. Leading applicants include companies like Lockheed Corp and Geely Holding Group, as well as academic institutions like Jinan University (fig 3).

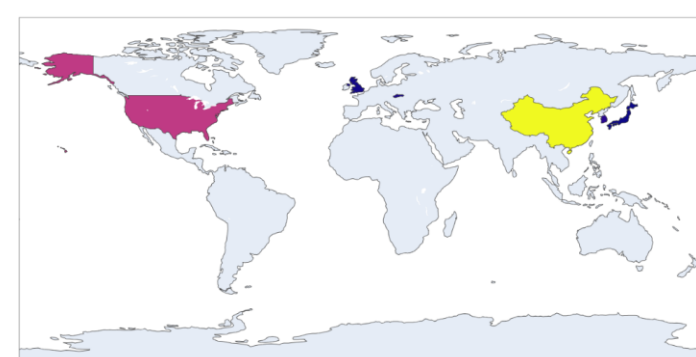


Figure 3. Geographical distribution by affiliation of authors

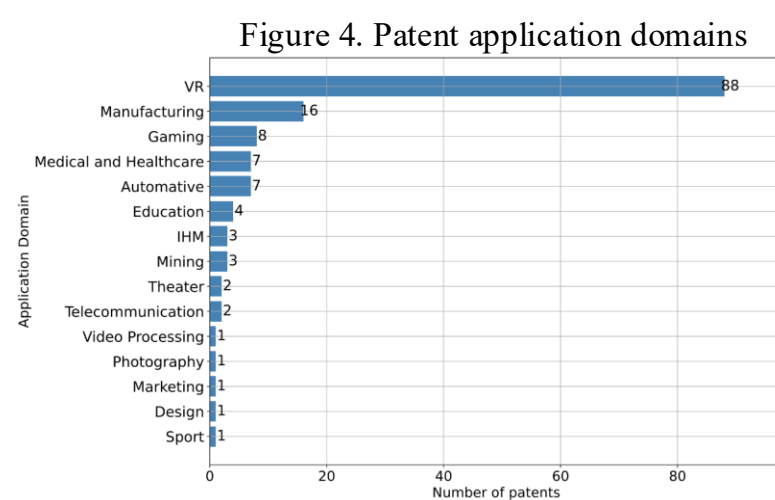


Figure 4. Patent application domains

The primary application domains are VR technology (88 patents), manufacturing (16 patents), and gaming (8 patents), followed by biotechnology, automotive, education, HMI, and more. The study uses CPC and IPCR classifications to detail CAVE innovations, particularly in physics-related fields like image processing and head tracking.

Cluster analysis reveals key areas: Audio and Video Systems (36 patents), CAVE Calibration (22 patents), Stereographic Rendering (21 patents), Tracking Systems (34 patents), Graphics Engine (35 patents), and entire CAVE Systems (4 patents) (Fig 5).

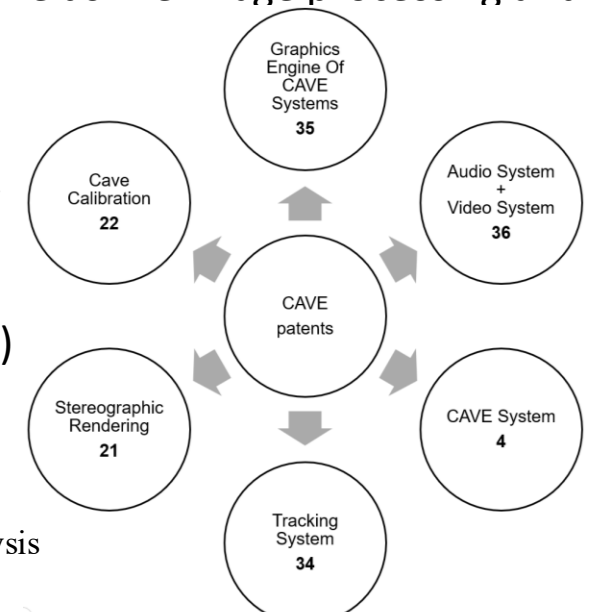


Figure 5. Cluster analysis

5. Discussion

RQ#1- Key developments include advanced audio/video systems, graphics engines, and motion tracking systems. These technologies enhance immersive experiences, real-time 3D image rendering, and natural user interaction. Human-body interaction devices and pose determination technologies further improve mixed reality capabilities.

RQ#2- Main application domains are VR technology, manufacturing, medical and healthcare, automotive, education, and gaming. Other sectors include human-machine interface, mining, theater, video processing, photography, marketing, and geosynchronization, demonstrating CAVE's versatility. Leading companies are Geely Holding Group Co LTD in China and Lockheed Corp in the USA. Both have significantly contributed to CAVE technology, with highly cited patents indicating key innovations. Academic institutions in the USA and China also play a crucial role.

RQ#3- Patents can be classified using CPC classification and CAVE components/system taxonomy. The study identifies 22 CAVE system variants and multiple application domains. Focus on under-explored areas like portable CAVE systems can address market needs and guide R&D efforts. Patent analysis reveals technological gaps, competitive dynamics, and influential patents.

6. Conclusion

This study analyzes the evolution and current state of CAVE technology through patent analysis. Findings show a significant increase in CAVE patents since 1992, indicating growing interest and advancements. Cluster analysis and Cooperative Patent Classification highlight key technological trends and competitive dynamics. Focusing on under-explored areas can drive innovation, reduce costs, and improve CAVE system accessibility. Applications span healthcare, education, manufacturing, and entertainment, demonstrating CAVE's versatility. The USA and China lead in patent filings. While current innovations enhance immersive experiences and user interaction, future research should explore more affordable and portable CAVE systems.