
From Gallery to Virtual Hub: The Evolution of Control Rooms in the Digital Era

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1 Introduction

The control room, often called the “gallery,” is the nerve center of broadcast media operations. It is where the coordination and management of live broadcasts occur, encompassing various technical and production elements to ensure seamless and high-quality content transmission Ivergård and Hunt, 2008. The control room houses multiple technologies, including video switchers, audio mixers, graphics stations, and monitoring systems Stan, Gheorghiu, and Timnea, 2013. It is staffed by directors, producers, vision mixers, and audio engineers Weinl, 2015. These individuals work together to oversee the real-time editing, mixing, and broadcasting of audio and video feeds, integrating pre-recorded segments, live inputs, and graphics to create a polished final output. As technology advances, control rooms have evolved from simple, analog setups to complex, digital environments, incorporating automation and computerization to enhance efficiency and reduce human error Stan, Gheorghiu, and Timnea, 2013. This continuous evolution has been crucial in maintaining broadcast media’s quality, reliability, and immediacy and adapting to the changing demands and advancements in the industry.

The control room is crucial in managing and coordinating live broadcasts, serving as the central hub where all the broadcast components converge Soseman, 2023b. Its importance can be highlighted through several vital functions. The control room ensures smooth transitions between different segments, cameras, and

audio sources, allowing directors and producers to make instantaneous decisions. This capability is essential for maintaining the flow and coherence of live broadcasts, whether they are news programs, sports events, or entertainment shows Key Code Media, 2021.

The control room team can quickly identify and rectify technical issues or errors by monitoring audio and video feeds, ensuring the broadcast maintains a high-quality standard Moroşanu et al., 2023. This function includes adjusting sound levels, correcting video exposure, and ensuring synchronization between audio and video. Additionally, the control room facilitates effective communication among various production team members, including camera operators, on-air talent, and technical staff. Through tools like intercom systems and talkback channels, the team can coordinate their actions to respond to real-time events and changes in the broadcast Soseman, 2023a.

Control rooms are critical in safety-critical contexts and broadcast environments, integrating various elements to create cohesive viewer experiences Mentler et al., 2021; Coleman, 2021. Modern control rooms utilize advanced automation systems and technologies to streamline operations, enhance efficiency, and reduce human error Mentler et al., 2021; Okopnyi et al., 2023. Integrating audio, video, and text information is crucial for generating semantically meaningful content and constructing effective index tables for large data Huang et al., 1999. In unexpected situations like breaking news, control rooms are essential for swiftly adapting broadcast plans and providing instructions

to on-air talent Coleman, 2021. Recent developments, accelerated by the COVID-19 pandemic, have led to the redistribution of work and increased automation in TV production, potentially inducing permanent changes in key work practices Okopnyi et al., 2023.

This paper aims to trace the evolution of the control room in broadcast media from its inception to the present day. The methodology combines historical analysis, technological review, and case studies to explore the evolution of broadcast control rooms and predict future trends. The historical analysis traces the development of control room technologies from their origins in radio broadcasting to the present day, providing a contextual foundation for understanding shifts in workflows and technological advancements. The technological review examines key innovations such as automation, artificial intelligence (AI)-driven processes, and extended reality (XR) as virtual, augmented, and mixed reality (VR/AR/MR), supported by existing studies and reports that highlight the impact of these advancements on control room operations. Additionally, case studies of modern broadcast environments and networks are used to demonstrate the practical application of these technologies, showcasing real-world examples of automated systems, virtual production, and cloud-based broadcasting. By integrating these methods, the paper documents past and present developments and engages in speculative forecasting, offering insights into how AI, XR, and digital workflows might shape the future of control rooms.

2 The Early Days of Broadcasting

The early days of radio broadcasting, from the 1920s to 1940s, marked a significant transformation in sound media Marc, 2000; VanCour, 2018. Control rooms were central to this evolving industry, characterized by simple analog technology and manual operation Dreher, 1928. Engineers and technicians managed audio levels and switched between sources using hardware like switchboards and early mixing consoles Dreher, 1928. This period saw the development of pioneering production methods and performance styles tailored to emerging electric sound reproduction technologies VanCour, 2018. Radio workers established best practices for programming, production techniques, and on-air talent, shaping the future of broadcasting and influencing broader shifts in music, drama, and public oratory VanCour, 2018. By the late 1940s, control rooms underwent significant changes, with cluttered racks and cabinets replaced by compact, functional control consoles that improved performance, ease of operation, and accessibility Monroe and Palmquist, 1948.

Radio control rooms were crucial in managing live broadcasts and pre-recorded segments and ensuring

uninterrupted transmission Dreher, 1928. Engineers were responsible for balancing audio levels, minimizing interference, and maintaining signal strength Monroe and Palmquist, 1948. The control room evolved from cluttered spaces filled with audio gear to streamlined, desk-sized consoles that improved performance and ease of operation Monroe and Palmquist, 1948. Sound effects, an essential element of radio programming, were often created live using various props and devices Sterling, 2013; Mott, 2005. The production process relied heavily on developing excellent listening skills, which were challenged by introducing digital audio technology and audio visualization on computer screens Barbour, 2004. Despite technological advancements, the art of radio production continued to depend on the ability to create compelling auditory experiences that engaged listeners' imaginations, maintaining radio's unique position as the 'ultimate auditory display' Barbour, 2004, p.1.

The evolution of audio technology in the late 20th century saw significant advancements in real-time sound processing and immersive audio systems. Early limitations in signal processing, acoustics, and human listening characteristics posed challenges for immersive audio development Kyriakakis, 1998. The 1930s marked a shift from real-time recording to post-production editing in cinema, enabled by optical sound cutting and improved noise control techniques Jacobs, 2012. Music studio technology progressed to include sophisticated microphones, mixing consoles, and digital audio formats, addressing various recording, broadcasting, and live performance needs Mores, 2018. Despite initial skepticism about digital technology's capabilities for instrumental music and real-time performance, significant advancements occurred within two decades. By the early 2000s, real-time music production and performance had evolved from primitive systems like the IRCAM 4X and Synclavier to more advanced technologies, challenging earlier doubts about their potential Machover, 2002.

The period saw significant advancements in radio technology and broadcasting. Guglielmo Marconi was pivotal in developing wireless communication, bridging science, commerce, and popular imagination Corazza, 1998; McCourt, 1989. Another key figure, Reginald Fessenden, made essential contributions to radio broadcasting and science from the late 1870s to 1932 Britain, 2004. The period they witnessed the transformation of radio from a private, directional medium to a public, omnidirectional one as institutions gained control over the technology McCourt, 1989. Hugo Gernsback, though often overlooked in broadcasting history, promoted radio experimentation and adoption among amateur hobbyists through his publications in the 1910s and 1920s Massie and Perry, 2002. These pioneers and their innovations laid the foundation for developing radio as a powerful communication medium, shaping its technical, cultural, and regulatory aspects.

3 The Rise of Television

The transition from radio to television in the 1950s marked a significant shift in media consumption, challenging the primacy of radio broadcasting Medhurst, Nicholas, and O'Malley, 2016; Fickers, 2012. This change required adaptations in content and presentation, as exemplified by quiz shows that moved from radio to television in Australia Moran and Aveyard, 2013. The advent of television forced other media to target niche markets, leading to changes in radio programming, film content, and newspaper reporting Baughman, 2006. This transition required significant technological and skill changes, as broadcasters needed to incorporate visual storytelling elements alongside traditional audio techniques Block, 2020. Control rooms evolved to handle these new requirements, incorporating more complex equipment to manage video feeds and coordinate live programming.

The advent of television brought significant changes to control rooms, introducing new video equipment and techniques. Cameras became central to broadcasting, capturing live footage that required real-time management Barker, 1991. Switchers, or vision mixers, were essential for seamlessly transitioning between video sources, enabling continuity editing and expanding television's representational repertoire Barker, 1991. Monitors were installed to provide visual feedback to directors and technical staff Norgaard and Jones, 1941. These advancements allowed for more dynamic broadcasts, with multiple camera angles and real-time editing enhancing storytelling capabilities Lyver and O'Neal, 2020. The integration of these technologies represented a significant leap from radio broadcasting, requiring the development of versatile control equipment to meet the technical and operational demands of television production Norgaard and Jones, 1941. Over time, control rooms continued to evolve, incorporating more sophisticated technologies and user interfaces to improve efficiency and capabilities Cochran, 1992.

The development of sophisticated switching systems for multi-camera television control rooms has led to significant advancements in live broadcasting. Research has focused on automating camera control and switching processes to reduce crew requirements and improve efficiency; however, a few notable examples can be seen throughout the years. For example, a touchscreen interface was introduced, allowing a single operator to control multiple cameras and determine broadcast views for sports events Foote et al., 2013. Moreover, an automatic shooting and switching system was introduced for American football, using image analysis to detect player positions and control camera movements Iguchi et al., 2002. Similarly, a modular automated system based on cinematographic rules was also created, utilizing markerless tracking and sound analysis to determine appropriate camera angles and switching times Daemen et al., 2016. Finally, an automatic cam-

era switching system for soccer games was also created, employing various algorithms to analyze scenes and select the best view while adhering to cinematic principles Najeeb and Ghani, 2020. These innovations have enhanced the ability to capture different perspectives and maintain smooth transitions in live broadcasts.

Live television broadcasts have been a significant aspect of the medium since the 1950s, offering viewers a sense of immediacy and excitement. The appeal of live TV lies in its indeterminacy, as events unfold in real-time, making them more thrilling than pre-recorded content Vosgerau, Wertenbroch, and Carmon, 2006. This unpredictability was exemplified in the live broadcasts of atomic bomb tests in the 1950s, which drew massive audiences despite technological challenges Thimons, 2020. The concept of "liveness" in television extends beyond technical aspects, encompassing viewers' beliefs and perceptions influenced by sound, image, and social context Bourdon, 2000. While live broadcasting has declined, it remains essential to understanding television's impact. It continues influencing various programming formats, from major events to game shows and news reports Bourdon, 2000; Allen, 2009.

The control room plays a crucial role in television production, with the director and technical team working together to create engaging content Coleman, 2021. In live broadcasts, the director focuses on artistic elements, making decisions about camera angles and shot composition while coordinating with remote performers and managing the overall vision Reeves, Greiffenhagen, and Perry, 2024; Neal, 2023. The technical director handles equipment operations and ensures the smooth implementation of the director's creative choices Neal, 2023. This partnership relies on distinct cinematographic grammar and careful timing to produce a seamless viewing experience Neal, 2023; Broth, 2004. The control room's organizational hierarchy and division of labor are designed to manage challenges of restricted informational visibility Reeves, Greiffenhagen, and Perry, 2024. Communication between the director and camera operators often follows a "proposal-acceptance" sequence, with timing crucial for establishing intersubjectivity in this mediated, asymmetrical interaction Broth, 2004. This collaborative effort aims to deliver compelling content while maintaining artistic quality Reeves, Greiffenhagen, and Perry, 2024.

Susan Murray's "Bright Signals" provides a comprehensive history of color television from 1928 to 1970, exploring its technical development, standardization, and cultural impact Murray, 2018; Yumibe, 2019; McBurney, 2020. The book examines how color TV transformed visual culture, disrupted existing notions of television, and revealed tensions between technology, consumerism, and human perception Murray, 2018. Murray's work draws on diverse fields, including color psychology, video aesthetics, and the study of subjectivity, to contextualize color TV's evolution Kane,

2020. The author traces the influence of colorimetry theories from Goethe to Ostwald on color broadcasting and highlights the role of standardizing boards like the Optical Society of America Yumibe, 2019. The book also discusses the competition between CBS and NBC in developing commercially viable color TV systems, culminating in the FCC's adoption of the National Television System Committee color standard in 1953 Yumibe, 2019; McBurney, 2020.

The coronation of Queen Elizabeth II in 1953 was a landmark event that showcased television's potential for mass communication and live broadcasting Richards, 2004. This historic occasion marked the first televised coronation, cementing TV's role as a national cultural form in Britain Clancy, 2019. The event highlighted the importance of television control rooms in managing live feeds and coordinating multiple camera angles. Despite initial reservations from politicians and the palace about live television potentially diminishing the monarchy's mystique, the broadcast encouraged viewers to engage as active royal "publics" Clancy, 2019. The coronation also played a crucial role in initiating pan-European cooperation for TV program exchange Dijk and Van Loon, 2003. The BBC utilized new technologies to uphold traditional monarchist and colonial ideas, portraying the Queen as a maternal figure and symbol of social unity Watson, 2023. This event set the stage for future live broadcasts of historical significance, demonstrating television's power to bring major events into people's homes.

4 Technological Advancements

The advent of digital technology in broadcast control rooms during the 1980s and 1990s revolutionized television production and management De Bruin, Smits, and Smits, 1999; Hopkins, 1996. This shift from analog to digital systems introduced higher precision and flexibility in audiovisual equipment Rubio and Sánchez, 2010. Digital technology enabled centralization, allowing fewer operators to control entire broadcasts, reducing staff and costs; however, this centralization led to increased technical responsibilities for remaining staff and potentially neglected visual aspects of broadcasts Weinl, 2015. The digital revolution also improved content quality and quantity while increasing accessibility to information; nevertheless, it introduced new challenges, such as the potential for information manipulation and technology dependence Sari, Sya'adah, and Amaliah, 2024. The transition to digital broadcasting culminated in the development of the Digital HDTV Grand Alliance system, which offered unprecedented flexibility and set the stage for future advancements in television technology Hopkins, 1996.

The transition from analog to digital television broadcasting marked a significant technological shift in the late 20th and early 21st centuries Kratochvil, 2008. This change brought numerous advantages, including

improved picture and sound quality, more efficient spectrum use, and new broadcasting possibilities like HDTV and mobile TV Kratochvil, 2008. The transition process was complex, involving policy issues such as digital transmission, interoperability, and copyright protection Castañeda, 2007. It required substantial infrastructure upgrades and spectrum management considerations to allocate the "digital dividend" – the spectrum freed up by the switch Rancy, Zilles, and Guitot, 2011. The implementation of digital television varied by country, with some nations, like Croatia, completing the transition ahead of schedule through well-designed public policies and government-led initiatives Andrijašević and Car, 2013. The shift to digital broadcasting represented a transformative period in television history, reshaping the medium's technological, economic, and cultural landscape.

The introduction of non-linear editing systems revolutionized television post-production, offering greater efficiency and creative flexibility than linear editing Morris, 2012; Korpi, Carbonara, and Young, 1996. Studies have shown that non-linear editing projects received higher scores and contained fewer mistakes, with students spending more time and adopting more sophisticated approaches using these systems Korpi, Carbonara, and Young, 1996. The transition to digital technology has led to improved image quality, resolution, and frame rates and the adoption of IP and open communication standards Bykov, 2023. Network Production Systems (NPS) have enhanced news video production efficiency by enabling transmission, editing, and archiving through networked systems Won, Choi, and Kim, 2011. These technological advancements have significantly impacted television production techniques, with modern textbooks emphasizing the latest production methods, including non-linear editing and HDTV Zettl, 2012. These innovations have transformed the television industry, improving production quality and streamlining workflows.

The widespread use of computers for editing and playback in the 1980s and 1990s transformed control room operations Ahanger, 2006. Computers enabled the digitization of video and audio content, allowing for more advanced editing techniques and streamlined workflows. Software-based editing platforms replaced traditional tape-based systems, making the editing process faster and more efficient Kratochvil, 2008. Computers also facilitated the integration of digital effects and graphics, enhancing the visual appeal of broadcasts. Additionally, computer-based playback systems allowed for more reliable and flexible broadcast schedule management, improving the overall efficiency of control room operations Cochran, 1992.

The digital revolution has significantly enhanced television broadcasting, offering superior video and audio quality compared to analog systems Jones et al., 2006. Digital TV provides higher resolution, sharper images, and improved color reproduction, while digital audio delivers more precise sound without the distort-

tions typical in analog recordings Rast, 2005. These advancements have set new standards for broadcast quality and enhanced viewer experiences. The transition to digital broadcasting has required substantial investments in equipment and infrastructure Jones et al., 2006. Furthermore, next-generation audio systems enable personalized and immersive experiences, allowing viewers to customize their audio preferences and enjoy enhanced surround sound Mehta and Ziegler, 2015. As the television industry continues to evolve in the digital age, it faces challenges and opportunities related to online streaming platforms, changing viewer preferences, and integrating social media Dhiman, 2023. These developments reshape content production, distribution, and consumption in the broadcasting landscape.

Satellite technology revolutionized television broadcasting in the late 20th century, profoundly impacting news coverage and international communication Kiesling, 1980. The advent of satellite networks enabled live transnational broadcasts, as exemplified by the 1967 "Our World" program Evans and Lundgren, 2016. This technology significantly expanded the reach of news organizations, allowing for real-time transmissions from remote locations with minimal equipment Livingston and Belle, 2005. The development of satellite and cable technology made international news more accessible to consumers, transforming the media landscape Friedland, 1992. Satellite technology, electronic newsgathering, and the global distribution of foreign correspondents became major influences shaping international news content on network television Larson, 1984. These advancements changed how news was gathered and transmitted and increased the likelihood of coverage from remote, less developed regions, ultimately reshaping the relationship between news media and policy Livingston and Belle, 2005.

The 1990s marked a transition period in control room technology, shifting from analog to digital systems The Science Museum Group, ND. CRT monitors became standard for displaying information Cochran, 1992, while graphics machines allowed for real-time integration of graphics with video feeds Smith, 1991. This era saw the emergence of hybrid human-system interfaces (HSIs), combining conventional and advanced technologies O'Hara, Stubler, and Kramer, 1997. The integration of digital systems presented both challenges and opportunities. A study comparing analog and digital turbine control systems (TCS) found that digital interfaces improved operator performance in certain tasks despite operators' preference for familiar analog systems Boring et al., 2017. The industry recognized the need for standardization in control system communication protocols to facilitate the integration of various manufacturers' systems Smith, 1991. These developments set the stage for future advancements in control room technology, including AI and VR applications Cochran, 1992.

The evolution of computer graphics in television production has been driven by the increasing reliance on

symbolic and imaginal communication, with digital electronics playing a crucial role Klimek et al., 1980. Innovations such as Chyron for on-screen computer-generated graphics (CGI) enhanced television broadcasts during the 1980s and 1990s. Chyron systems allowed broadcasters to overlay text, graphics, and animations on live video feeds, adding a new dimension to television content. CGI allows real-time tracking and visualization of objects in sports broadcasts, improving viewer engagement Cavallaro et al., 2011. These graphical enhancements have aided information retention and processing for viewers, especially younger audiences Fox et al., 2004. These systems aim to enhance viewer understanding by supplementing broadcasts with externally sourced and summarized knowledge, catering to audiences with varying levels of background information Hemsley et al., 2013. The ability to create and manipulate graphics in real-time was a significant advancement, requiring skilled operators and sophisticated equipment in the control room.

The evolution of video editing from the 1980s to the early 1990s was marked by a transition from linear to non-linear systems. Editors initially worked with physical tapes and video tape recorders (VTRs), employing edit controllers for timing and synchronization Silcock, 2007. This labor-intensive process involved manual shuttling through tapes, marking in and out points, and splicing segments together Crittenden, 2003. The editing procedure was crucial in shaping productions' narrative and visual flow, with editors selecting, arranging, and modifying shots to refine content and form Falkenberg, 1967. As digital technologies emerged, the industry gradually shifted towards more efficient non-linear editing systems, though physical tapes remained prevalent for some time Jódar-Marín, 2017. This transition period saw the coexistence of traditional tape-based methods and emerging digital techniques, reflecting the industry's adaptation to technological advancements in post-production processes.

The digital revolution in broadcasting during the 1980s and 1990s brought significant changes to control room operations, but key roles remained crucial. Vision mixers, responsible for selecting and transitioning between video sources, played a central role in live TV production, collaborating closely with camera operators to create coherent broadcasts Engstrom et al., 2008. Audio mixing consoles, essential for managing sound levels and quality, underwent technological advancements with the introduction of digital systems and computer control Harris et al., 1989. Despite the potential for de-manning and deskilling offered by digital production technologies, their full impact was not realized until the late 1980s, following the termination of national collective bargaining that had previously regulated minimum crewing levels McKinlay and Quinn, 1999. These developments required skilled professionals to operate advanced digital equipment and maintain high broadcast quality standards, highlighting the continued importance of specialized roles in

the evolving broadcasting landscape.

5 Modern Control Rooms

The 2000s to the present day have witnessed a remarkable transformation in control rooms, characterized by the widespread adoption of automation and advanced digital technologies Dhir, 2004. Modern control rooms are now highly sophisticated and equipped with state-of-the-art technology to streamline operations, enhance efficiency, and ensure seamless broadcasts. Integrating automation and computerization has fundamentally changed how control rooms function, reducing the need for manual intervention and minimizing human error. This era has consolidated multiple tasks into more compact, user-friendly interfaces, making control room operations more efficient and flexible.

The shift towards automation and integration in control rooms has revolutionized broadcasting. Automation systems can now manage tasks requiring manual input, such as camera switching, audio mixing, and graphics insertion. This automation has been achieved through advanced software and hardware solutions that work together seamlessly. Integration is critical to this transformation, as different systems and components must communicate effectively to ensure smooth operations Huf, Salvadori, and Siqueira, 2016. The result is a more streamlined workflow, where repetitive tasks are handled automatically, freeing up human operators to focus on more critical aspects of production.

The shift towards automation and computerization has been one of the most significant changes in control rooms over the past two decades. Automation systems handle various routine tasks, such as scheduling, playout, and even some aspects of live production Tsuda et al., 2003. This shift has been driven by the need to improve efficiency, reduce costs, and enhance the reliability of broadcasts. Computerization has enabled advanced software applications that can control multiple aspects of the broadcast from a single interface, making the entire process more cohesive and manageable.

Sophisticated software like the Electronic News Production System (ENPS) Todorović, 1991 has become a cornerstone of modern control rooms. ENPS allows for comprehensive news production management, integrating script writing, rundown creation, and media asset management into a single platform. This software enables real-time collaboration among journalists, producers, and technical staff, ensuring everyone works with the same updated information. Such software has streamlined news production workflows, enhancing the speed and accuracy of news delivery.

The importance of IP (Internet Protocol) technology in modern control rooms cannot be overstated Simpson, 2013. IP technology has enabled the transition from traditional broadcast infrastructure to more flex-

ible and scalable network-based systems. IP allows for transmitting audio, video, and control signals over standard IP networks, facilitating remote production and reducing the need for extensive physical cabling. IP technology has also enabled greater flexibility in content delivery, allowing broadcasters to distribute content across multiple platforms, including traditional TV, online streaming, and mobile devices.

Integrating software for seamless operation has been a critical advancement in modern control rooms. Digital playout systems, for example, automate the process of scheduling and broadcasting content Hussein, 2015. These systems ensure that the right content is played at the right time, reducing the risk of human error and ensuring a smooth broadcast experience. Such systems are integrated with other software platforms, like ENPS, to streamline the production and playout process. This integration ensures that all components of the broadcast workflow work together seamlessly, from content creation to final delivery.

Real-time graphics and virtual sets have become standard features in modern control rooms, enhancing broadcasts' visual appeal and flexibility Chanpum, 2023. Real-time graphics systems allow for creating and inserting dynamic graphics during live broadcasts, such as lower thirds, weather maps, and sports scores. Virtual sets use green screen technology and real-time rendering to create immersive environments that can be changed on the fly. These technologies provide broadcasters with greater creative flexibility and enable the production of visually engaging content without the need for physical sets.

Multi-functional consoles and touch-screen interfaces have simplified the operation of modern control rooms Nickel, 2023. These user-friendly interfaces allow operators to control multiple aspects of the broadcast from a single console, including video switching, audio mixing, and graphics insertion. Touch-screen interfaces provide intuitive controls, making it easier for operators to manage complex tasks quickly and accurately. Consolidating functions into a single interface reduces the complexity of control room operations and allows more efficient use of space and resources Cremona and Kavakli, 2023.

In modern control rooms, redundancy and backup systems are essential to prevent failures and ensure uninterrupted broadcasts Rudman, Osenkowsky, and Pollet, 2017. Redundancy involves having duplicate systems and components that can take over in case of a failure. Backup systems provide additional layers of security, ensuring that there are always alternative paths for audio, video, and control signals. These systems are critical for maintaining the reliability and integrity of broadcasts, especially during live events where any interruption can have significant consequences. Modern control rooms are designed with multiple layers of redundancy and backup systems to safeguard against technical issues and ensure continuous operation.

6 Future Trends

The integration of AI in broadcast technology is revolutionizing video production and consumption. AI enables innovative approaches in content creation, personalization, and efficiency Huang et al., 2023. It facilitates deeper audience understanding through demographic analysis and recommendation algorithms, enhancing viewer engagement Azahra, Yuningsih, et al., 2024. AI supports various tasks in television production, including increasing video resolution, evaluating quality, and enriching metadata Panda and Meher, 2024; Mrak, 2019. The BBC has explored AI's potential in live event coverage, developing algorithms for automatic framing, sequencing, and shot selection, allowing for expanded coverage with minimal crew Wright et al., 2023. AI also contributes to advancements in image enhancement, colorization, and compression efficiency Mrak, 2019. While AI significantly benefits the broadcasting industry, ethical concerns regarding data privacy and security remain important considerations Azahra, Yuningsih, et al., 2024. AI is transforming traditional production tasks, potentially revolutionizing content creation and delivery more cost-effectively Mrak, 2019.

AI increasingly impacts creative industries, with applications spanning content creation, information analysis, enhancement, and data compression Anantrasirichai and Bull, 2022. AI technologies, including machine learning algorithms like convolutional neural networks (CNNs), generative adversarial networks (GANs), and recurrent neural networks (RNNs), are being adopted to augment human creativity rather than replace it Anantrasirichai and Bull, 2022. Integrating AI into creative processes raises technical challenges, such as operating with limited data and processing multiple modalities simultaneously Amato et al., 2019. While AI has made significant strides in creative applications, including generating entire movies and music albums, its potential to independently win awards for original creations remains limited Anantrasirichai and Bull, 2022; Amato et al., 2019. The use of AI in artistic creation also prompts philosophical questions about consciousness in machines and ethical implications in creative contexts Crimaldi and Leonelli, 2023.

In a case study of AI in news production Munoriyarwa, Chiumbu, and Motsaathebe, 2023, Munoriyarwa et al. investigated how AI impacted production and created three categories in which these impacts could be viewed. They identified three ways AI is adopted: holistic, exclusively technological, and task-specific. Using AI can also allow for automated use for various tasks. An example of this can be seen in Stoll et al., 2023, where Stoll et al. created a system for amateur shoots. The proposed system uses cropped images from a wider shot to create close-ups framed in a more professional, concise framing. To allow for the camera switching, a combination of methods, such as plot analysis and professional editing rules, provide

the information for an automatic editing script.

Regarding how an audience engages and interacts with television productions, AI offers a large advantage in creating personalized experiences. Data-driven approaches have been collected in a survey by Nixon et al. in Nixon et al., 2022 where they identify several areas that AI-driven personification could impact. These include the ability to fragment videos temporally and detect objects within them, classify and annotate media assets, find relevant content through cross-modal representation and retrieval, and transform content through video summarization, highlight detection, super-resolution, and aspect-ratio adaptation. Additionally, AI can personalize in-stream content by changing content or inserting content within streams. These processes will also continue to improve with the development of foundation models that incorporate the process of segmentation and semantic understanding Wang et al., 2024. A system to engage the interest of an audience was developed by Dudekula et al. Dudekula et al., 2023 where a camera was able to identify the facial characteristics of a user and apply this information to the user profile to create recommendations based on that user profile. A development of this work could be to gauge the user's interest based on facial expressions and dynamically update recommendations accordingly, as investigated by Liya Lin Lin, 2022.

Using AI can also have several benefits for audiences, especially regarding interactive experiences. In Xu et al., 2024, Xu et al. found that children who watched an interactive educational program performed better on a post-test than non-interactive and pseudo-interactive versions. The use of interactivity can also be applied to film. In Tong et al., 2021, Tong et al. investigate the use of AI methods to recognize human motion and pose; in the paper, the reason for doing so is to create more realistic animation; such an understanding is also necessary to create interactive responses to the audience. Pavlakos et al. Pavlakos et al., 2022 created an automated approach that analyzes an entire season of a TV show and aggregates information in a 3D environment. Using this approach, they were able to construct a 3D model of the environment, calculate camera information, and determine the static 3D scene structure and body scale. This could have several applications, including re-identification, gaze estimation, cinematography, and image editing, but it would also offer additional benefits in an interactive production. In Li and Wang, 2024, Li et al. show how the reconstruction of TV and film scenes could be implemented. While this process offers benefits in understanding the framing of devices in a scene, this approach also offers greater benefits in constructing immersive virtual spaces.

How this understanding could be applied to interactive programs has been investigated by Yao Yao, 2023, describing the idea of a virtual host engaging with an audience. Key technologies such as 3D virtual engine architecture, image recognition, and motion capture

are enhancing the capabilities of AI virtual hosts in TV programs Yao, 2023. These advancements are also being applied to Virtual YouTubers, with research exploring using PIFuHD for 2D to 3D character transformation and single-camera motion capture Xu, 2021. The success of virtual idol groups like A-SOUL demonstrates the potential of combining 5G networks with superior motion capture technology and visual design Tong et al., 2021.

XR technologies are revolutionizing television production and viewer engagement. Social VR platforms enable users to interact in shared virtual environments, offering new possibilities for live TV experiences Langa et al., 2021. These platforms support real-time integration of remote users, seamless incorporation of various media formats, and low-latency interactions Langa et al., 2021. Studies have shown that users perceive photo-realistic Social VR experiences as similar to face-to-face scenarios, appreciating the ability to sense emotions and communicate effortlessly Montagud et al., 2022. The development of VR learning media using WebXR asset management has also been explored, highlighting VR's potential as an interactive educational tool Matahari, 2022. Ongoing research focuses on achieving a true sense of "being there together" through volumetric video conferencing, addressing challenges in production processes and user experience quantification Cesar, 2023. These advancements demonstrate the growing potential of XR technologies in reshaping media consumption and interaction.

Virtual production (VP) is revolutionizing filmmaking by integrating real-time rendering, game engines, and LED walls to create immersive environments Perkins and Echeverry, 2022; Hendry et al., 2024. This technology allows filmmakers to visualize and manipulate digital assets in real-time, enhancing creative exploration and decision-making Hendry et al., 2024; Silva Jasauí et al., 2024. VP enables the seamless combination of live-action and virtual elements, optimizing production costs and expanding creative possibilities Perkins and Echeverry, 2022. Educational tools like cineDESK facilitate learning and experimentation with VP techniques, helping students develop visual language Hendry et al., 2024. The VP studio concept transforms traditional filmmaking workflows, fostering collaboration between different production stages and disciplines Kavakli and Cremona, 2022; Silva Jasauí et al., 2024. As VP technology becomes more accessible, it offers potential for various production scales, from indie films to large studios, and is poised to become a game-changer in the film industry Silva Jasauí et al., 2024; Kavakli and Cremona, 2022.

VP has emerged as a transformative approach in film and television, combining live-action and computer graphics in real-time Iseli, Loertscher, and Thomas, 2022a. Swords and Willment, 2024 identify three primary forms of VP: live-action green/bluescreen, full-scale virtual environments, and LED screen-based virtual sets. The evolution of VP is evident in films like

"Avatar" (2009), "The Jungle Book" (2015), and "The Lion King" (2019), showcasing advancements in digital modeling and game engine integration Li et al., 2022. VP offers benefits such as increased flexibility for directors, potential carbon emission reductions, and improved production efficiency Swords and Willment, 2024; Wan, 2024. However, challenges remain, including composition artifacts in green-screen procedures with moderate resources Iseli, Loertscher, and Thomas, 2022b. Despite these challenges, VP is expected to continue developing and expanding into other industries, potentially revolutionizing traditional production processes and inspiring new creative possibilities Wan, 2024.

Using game engines and VR technologies in film production offers significant benefits for pre-visualization and remote collaboration. Real-time 3D engines enable flexible and efficient pre-visualization, addressing key challenges in animation and camera control Nitsche, 2008. Virtual production techniques, combining game engines with immersive technologies, foster creativity, collaboration, and decision-making while increasing efficiency Bodini et al., 2023. These tools facilitate remote exploration of locations and content co-creation, particularly for small and medium-sized productions. 3D game engines can be utilized to develop virtual design review systems, enhancing visualization and collaboration among designers and reviewers Shiratuddin and Thabet, 2011. Furthermore, collaborative pre-visualization tools in VR allow multiple filmmakers to plan scenes together remotely, reducing the workload in later production stages Ardal et al., 2019. These advancements in virtual production contribute to more effective previsualization, streamlined workflows, and improved remote collaboration in filmmaking.

To connect these nascent technologies in the control room of the future, 5G has revolutionized television broadcasting, enabling cloud-based production and transmission of high-quality content Wang and Gong, 2021. This shift reduces costs, allows quick deployment, and facilitates rapid response to events. 5G networks support remote content production and improve signal transmission and distribution Lustica and Bozek, 2019. Advanced applications like free-viewpoint video can be efficiently produced and streamed in real-time using 5G infrastructure, though some limitations still exist Pérez et al., 2022. The integration of 5G with cloud computing, AI, and other emerging technologies promotes all-media cloud-based production and broadcasting Wang and Gong, 2021. This approach offers ultra-low latency, high bandwidth, and flexible resource allocation Keltsch et al., 2018 As 5G continues to evolve, it promises to unlock new potentials in the media industry, enabling more flexible, cost-effective production workflows and enhancing viewer experiences.

7 Conclusion

The evolution of broadcast control rooms has reached a pivotal point with the integration of AI automation, IP-based workflows, XR technologies. These advancements significantly depart from traditional, infrastructure-heavy setups, enabling more streamlined, flexible, and efficient production environments. XR-driven virtual galleries, combined with AI-enhanced tools, reduce physical constraints and provide dynamic interaction and customization options tailored to the unique demands of production roles, from vision mixers to sound engineers.

The transition from analog to digital workflows revolutionized content accessibility, and now AI-driven personalization is set to transform how audiences engage with media. Intelligent agents embedded in broadcasts offer more interactive, tailored news consumption opportunities, enhancing the viewer's understanding of content. Additionally, the widespread adoption of IP workflows opens up new possibilities for remote collaboration, decentralizing control room operations and offering production teams greater flexibility and efficiency.

Cloud-based solutions further complement this shift, enabling the seamless integration of AI models for ongoing process optimization. As the broadcast industry continues to adapt to these technologies, the future promises a more agile, interactive, and cost-effective production approach, transforming how content is created, distributed, and consumed. The control room of the future will not only enhance operational efficiency but also deepen the personalization and interactivity of viewer experiences, driving the next wave of innovation in broadcast media.

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