Lifecycle Management of Construction Assets Using BIM and VR/AR

Dr. Immanuel John Samuel,
Project Engineer, Garney Construction, Virginia, USA
ORCiD – https://orcid.org/0000-0001-6501-6263

Abstract

BIM (Building Information Modeling) is a widely adopted industry standard for the AEC sector that enables an effective way of managing data and information throughout a project lifecycle. By integrating other technologies such as VR (Virtual Reality) and AR (Augmented Reality) with BIM, various functions of BIM can be enhanced, such as virtual walkthrough, schedule visualization, clash detection, and as-built modeling. Moreover, asset management functions during the maintenance and operation phase of facilities and infrastructure can also benefit from this kind of integration. This paper will provide a comprehensive review of several emerging technologies regarding (1) technological advancements reflected by software and hardware development, (2) applications in the design, construction and asset management through integration with BIM in all phases of projects, and (3) current state of research and practice. It will also identify some limiting factors that hinder VR/AR from further deployment, such as lack of GPS accuracy, complexity in development and unclear data security. Furthermore, this paper will present the benefits of integrating VR/AR technologies with BIM throughout the project lifecycle.

Keywords: Building information modeling, Emerging technologies, Geographic information system, Internet of things, Cloud technology.

1. Introduction

In the rapidly evolving landscape of the Architecture, Engineering, and Construction (AEC) sector, the adoption of innovative technologies has become instrumental in enhancing project efficiency and overall asset management. This paper delves into the intricate realm of Building Information Modeling (BIM) and its integration with Virtual Reality (VR) and Augmented Reality (AR), offering a profound exploration of the synergies between these technologies for comprehensive lifecycle management of construction assets.

The integration of VR and AR with BIM introduces a paradigm shift in the way data is managed throughout the project lifecycle, offering advanced functionalities such as virtual walkthroughs, schedule visualization, clash detection, and as-built modeling. Notably, this integration extends beyond the project's construction phase, demonstrating its potential in optimizing asset management during the maintenance and operation of facilities and infrastructure.

This paper unfolds in three distinct sections: firstly, it conducts a thorough review of the technological advancements represented by both software and hardware development in this domain. Secondly, it explores applications across the design, construction, and asset management phases, highlighting the seamless integration of emerging technologies with BIM. Lastly, it offers a comprehensive overview of the current state of research and practice in this dynamic field.

While recognizing the transformative potential of BIM and VR/AR integration, the paper sheds light on certain limiting factors that currently impede the widespread deployment of VR/AR technologies. Issues such as GPS accuracy, developmental complexities, and data security concerns are identified, providing valuable insights for both researchers and practitioners.

In conclusion, this paper underscores the undeniable benefits of synergizing VR/AR technologies with BIM throughout the project lifecycle. By examining the interplay of these technologies, it aims to contribute to the ongoing discourse on the future of construction asset management, offering a roadmap for harnessing the full potential of emerging technologies in the AEC sector.

2. Review of BIM and VR/AR Technologies

Engineers and architects continually innovate construction techniques. In the digital age, computer 3D modeling transforms communication, yet a gap persists in site integration. Wearable tech, gaming, and augmented reality now bridge this gap, revolutionizing construction technology.

2.1 Hardware Innovations in VR/AR

Illustrating pivotal moments since the 1950s, Figure 1 encapsulates the evolutionary journey of Augmented Reality (AR). Initiated by Heilig in the early 1950s, virtual reality research aimed to create a versatile simulator device, resulting in the 1962 patented Sensorama—an immersive apparatus integrating a 3D video simulator, stereo sound, aroma, wind effects, and motion effects [Heilig, 1962]. The Head Mounted Display (HMD) concept, conceived by Heilig in 1960, materialized in 1966 as "The Sword of Damocles" by Ivan Sutherland [Sutherland, 1965].

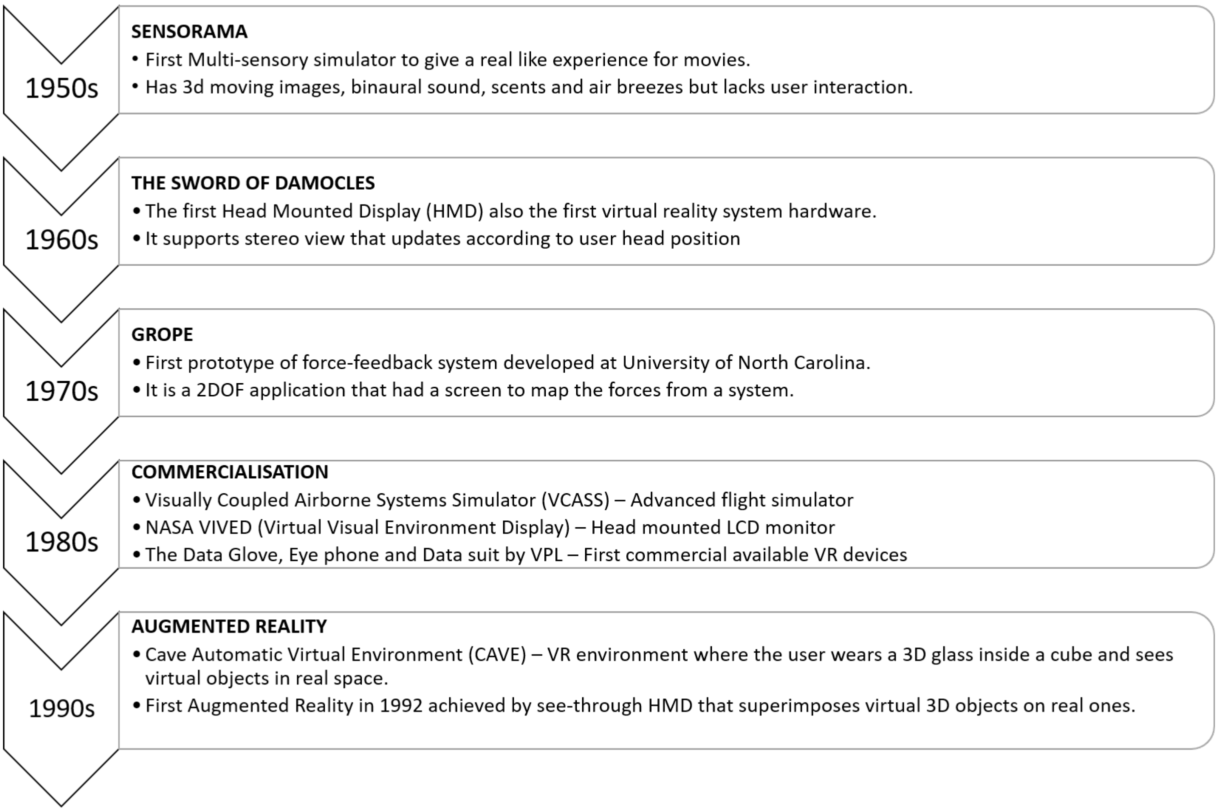

Figure 1. Evolution of Virtual Reality

[Based on Van Krevelen & Poelman, 2010; Mazuryk & Gervautz, 1996]

Sutherland's "Ultimate Display" foresaw touch integration, realized by Batter and Brooks in 1971, paving the way for contemporary haptic devices [Brooks Jr, 1971]. The U.S. Army leveraged virtual reality in the 1977 VCASS flight simulator [Kocian, 1977]. NASA's 1988 VIVED simulator showcased increasing immersion ["NASA's Virtual Workstation: using computers to alter reality," 1988], and the "Virtual Fixture" marked the inception of Augmented Reality in 1993 [Rosenberg, 1993].

Terminology ambiguity persists, delineated by the Virtuality Continuum [Chavan, 2016]. Virtual reality constructs an imaginary environment, while augmented reality overlays information [Sidiq, Lanker, & Makhdoomi, 2017]. Augmented virtuality integrates real-world scenes, seen in applications like the IKEA mobile shopping experience [Regenbrecht et al., 2004].

Figure 2. Virtuality Continuum

[Based on Milgram et al., 1995; Carrozzino & Bergamasco, 2010]

2.2 Software Developments in BIM

Building Information Modeling (BIM) stands as an intelligent, model-based process facilitating efficient planning, design, construction, and management of buildings and infrastructure (Autodesk). It serves as a digital representation encompassing the physical and functional aspects of various built objects, ranging from buildings and bridges to roads and process plants (ISO 12911).

Within the construction industry, a multitude of stakeholders engage in data-intensive processes throughout the project lifecycle. Coordinating and maintaining up-to-date data is imperative for successful project management. Faced with low productivity and unsustainable practices, the construction sector has increasingly turned to BIM adoption. Despite BIM's introduction in the early 1980s [RUCAPS (Riyadh University Computer Aided Production System), 1984; Vectorworks, 1985; Sonata, 1986; Pro/ENGINEER, 1988; ArchiCAD for iOS, 1987; Building Decision Advisor, 1993], widespread utilization only gained traction with the introduction of Revit in 2000. However, the construction industry still grapples with significant challenges in effectively implementing BIM.

A key requirement for successful project outcomes is a unified platform enabling communication and information exchange among stakeholders for collaborative decision-making. While BIM has proven effective for product-oriented solutions, addressing the needs of process-oriented solutions poses challenges. Emerging technologies such as GIS-based BIM, Cloud BIM, BIM integrated with the Internet of Things (IoT), and Augmented Reality with BIM have surfaced as solutions. Leveraging their high-performance capabilities and accessibility, these technologies contribute to the development of effective BIM governance solutions, offering promising avenues for improved collaboration and communication among diverse project teams.

3. Applications Across Design, Construction, and Asset Management

The virtual reality applications prevent the user to communicate with the real world when he is immersed in the virtual world, hence the application of VR is limited to simulated trainings. AR overcomes this limitation and extends its application in different phases of building and infrastructure projects.

3.1 Application in Design

Planning phase includes preparing the design, budget and schedule for the project. Poor planning may cause rework and increase the project cost and time significantly. Frequent design changes in planning phase is identified as the major construction waste [Nagapan, Sasitharan, & Abdul Rahman, 2011]. The main reasons for design changes are poor working drawings, the owner's misunderstanding of the design, and errors in design [Alaryan et al., 2014].

Constructability analysis is a process which can maximize the efficiency of planning. It is achieved by collective knowledge and experience of all the project stakeholders. The 4D model and design details are discussed among stakeholders to make necessary changes prior to construction. However, lack of communication between stakeholders and Level of Details (LoD) required for each stakeholder are some of the major drawback for this process [Boton, Kubicki, & Halin, 2013]. The Virtual Design and Construction (VDC) process makes all the models digitally accessible. It helps to bring all the stakeholders from remote location together in Virtual Reality model [VRcollab]. By walking through the 4D-BIM model in VR, constructability analysis contributes to productive planning of a project [Smith J.G., 2016]. VDC for collaborative decision making by using cloud-based multiusers VR system helps for efficient planning [Du.j et al., 2017,2018]

McCarthy Building Companies developed their own virtual reality technology powered by BIM CAVE and Oculus Rift. McCarthy used this VR technology to design a hospital in Los Angeles. After completing the preliminary design, they used the specialized knowledge of the doctors and physicians to design the facility according to their needs. With the help of virtual reality, the designers and the doctors were able to walk through the design and make necessary changes before it was executed. This eliminated the rework and prevented the cost and schedule overrun [John Gaudiosi, 2015].

3.2 Application in Construction

The implementation of construction projects on-site involves the engagement of manpower, materials, and equipment, leading to frequent schedule and budget overruns. Workplace accidents contribute significantly to these challenges, with 21% of occupational accidents occurring in the construction industry, as reported by OSHA in 2016 [Commonly Used Statistics, 2016]. The primary factors contributing to these accidents are the incorrect use of personal protection equipment and the disregard for hazard warning signs [Cheng et al., 2010]. This is exacerbated by a lack of safety training and skilled labor [Tam et al., 2004; Sawacha et al., 1999]. While safety in the construction industry has improved over the last two decades, it remains a leading cause of workplace accidents, alongside the manufacturing industry [Hinze et al., 2013; Macedo & Silva, 2005].

Traditional training methods, involving 2D demonstrations and videos, fall short of effectively preparing workers for real-time construction environments, especially with the increasing influx of migratory workers [Park & Kim, 2013]. Virtual Reality (VR) simulations offer a solution, allowing laborers to experience and respond to real-time situations without the risk of injury [Tatić & Tešić, 2017]. Notably, the VRTEX virtual reality welding training system has demonstrated a 23% faster learning rate, enhanced muscular memory, and improved motoric patterns, showcasing the potential for virtual reality in skill development [Postlethwaite, 2012].

In addition to enhancing safety, Virtual Reality (VR) and Augmented Reality (AR) technologies offer transformative applications in construction activities. VR simulations tailored to specific construction scenarios provide realistic training, while AR simplifies certain tasks, reducing costs and time. For instance, AR facilitates layout marking, excavation, and the placement of precast elements, streamlining these activities [Delhi & Singh, 2019; Chalhoub & Ayer, 2019; Shin & Dunston, 2008]. AR headsets enable the visualization of Building Information Model (BIM) data over the real world, eliminating the need for specifications and drawings on-site [DAQRI, 2016]. Research indicates that construction workers using BIM with AR complete tasks twice as fast as those using traditional paper drawings [chu et al., 2018].

Figure 3. Worker inspecting a site and his view
[Based on "Top 5 construction technologies to keep you safe," 2018]

AR's potential applications extend to construction inspectors, offering efficiency, higher accuracy, and time and cost savings. By accurately tracking user locations, AR systems enhance the inspection process, making it more streamlined and less labor-intensive [Kim et al., 2013]. Despite its potential, AR's usage in construction remains limited [Omar & Nehdi, 2016]. Combining AR with mobile computing presents a powerful tool for monitoring construction projects, offering substantial savings in cost and time [Zaher et al., 2018].

AR is also employed for virtual walkthroughs of as-built models, performance visualization, and progress monitoring in building and infrastructure projects [Golparvar-Fard et al., 2009; X.Wang et al., 2013]. Additionally, AR assists in damage assessment of assets, with studies at the University of Michigan utilizing the ARMOR AR system for safety helmets [Behzadan et al., 2015]. The application of AR as an inspection tool in tunnel construction in China demonstrated a 25% reduction in overall inspection time [Zhou, Luo, & Yang, 2017]. These advancements highlight the transformative potential of AR in improving safety, efficiency, and overall project outcomes in the construction industry.

3.3 Application in Asset Management

The operational and maintenance crew responsible for the upkeep of constructed buildings and infrastructure require integrated information for efficient work order execution [Akcamete et al., 2011]. Facility Document Repositories traditionally store detailed drawings, plans, field reports, and guidelines, consuming considerable space. Building Information Modeling (BIM) systems have been adopted to manage these documents digitally; however, 50% of onsite maintenance time is still spent on pre-maintenance preparations, involving document identification and jobsite location [Lee & Akin, 2011].

Augmented Reality (AR) addresses this issue, simplifying the maintenance process. A case study at Ruhr University, Bochum, demonstrated AR's efficacy in repairing damaged smoke detectors. The facility operator generates a digital work order with navigation instructions, accessible via the service engineer's mobile device. Upon reaching the jobsite, the engineer scans a marker to receive further repair instructions, enhancing real-time assistance [Koch et al., 2014].

In the maintenance phase, periodic inspections are crucial for preventive maintenance to reduce structural redundancy, minimize the risk of sudden failure, and enhance structural longevity. Traditional inspection tools, limited to human senses, a tape measure, a hammer, and, in some cases, tablets and digital cameras, have inherent limitations like low productivity, data errors, and a reliance on skilled labor [Moore et al., 2001; Phares et al., 2004; Wang et al., 2007; Zhu, German, & Brilakis, 2010]. New technologies (robotics, Lidar, UAV) collect objective data but still require human validation [See & Druary, 2017].

Augmented Reality fills the gap by providing an interface for bridge inspectors to access previous reports and relevant information corresponding to the structural element under inspection. The AR interface can measure delamination, crack widths in concrete bridges, and transverse and vertical displacement of structural members [Antony et al., 2006; Moreu et al., 2017, 2019]. Integrating BIM with AR enhances these advantages, creating an AR simulator where inspectors can familiarize themselves with the structure before inspection, mark points for checking, and reduce onsite inspection time [Salamak & Januszka, 2015]. The AR interface enables image capture for damaged members, and annotations made on images can be transferred for further analysis [Dang & Shim, 2019; Napolitano et al., 2019]. Additionally, semi-supervised machine learning algorithms assist inspectors in identifying the severity of cracks [Karaaslan et al., 2019].

4. Summary and Conclusion

This paper provides a comprehensive review of literature on Building Information Modeling (BIM), virtual and augmented reality (VR/AR) research, and their implications in construction and infrastructure systems spanning the last three decades. The review underscores that while the primary application of virtual reality (VR) is as a visual support tool, augmented reality (AR) exhibits a broader scope and more diverse applications. AR, with its ability to track user location and movements, emerges as an ideal tool for inspection and environments requiring access to location-specific data. Recent advancements in AR headsets, with location accuracy below 1 cm even in indoor environments, showcase the evolution depicted in Figure 4.

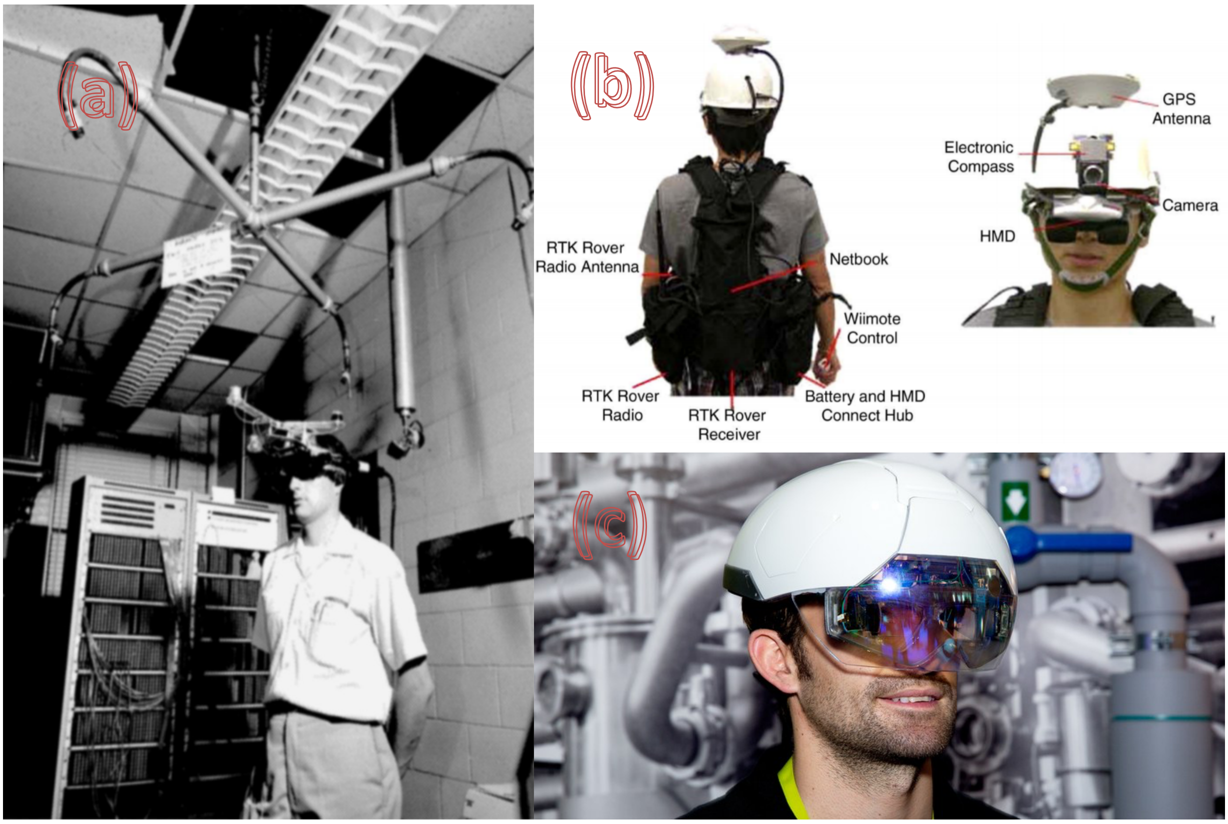

Figure 4. From Left HMD's (a)The sword of Damocles 1962 (b)Rover 2007 (c)Daqri Smart Helmet 2016

Figure 4 illustrates the progression of head-mounted displays (HMDs), from the Sword of Damocles in 1962 to the Rover in 2007 and the Daqri Smart Helmet in 2016. Modern HMDs benefit from microprocessors and nano sensors, making them more compact and usable than their predecessors, thereby opening up a wide range of applications across various domains. Research before 2000 primarily focused on simulation purposes, with limited exploration of commercial applications in civil engineering until around 2005, as depicted in Figure 5. The development of ARkit and ARcore further expanded research beyond architectural applications. Notable companies like DAQRI and Trimble continually enhance HMD hardware for civil engineering applications, as indicated in Table 1, which outlines the major research and applications of AR/VR in civil engineering over the years.

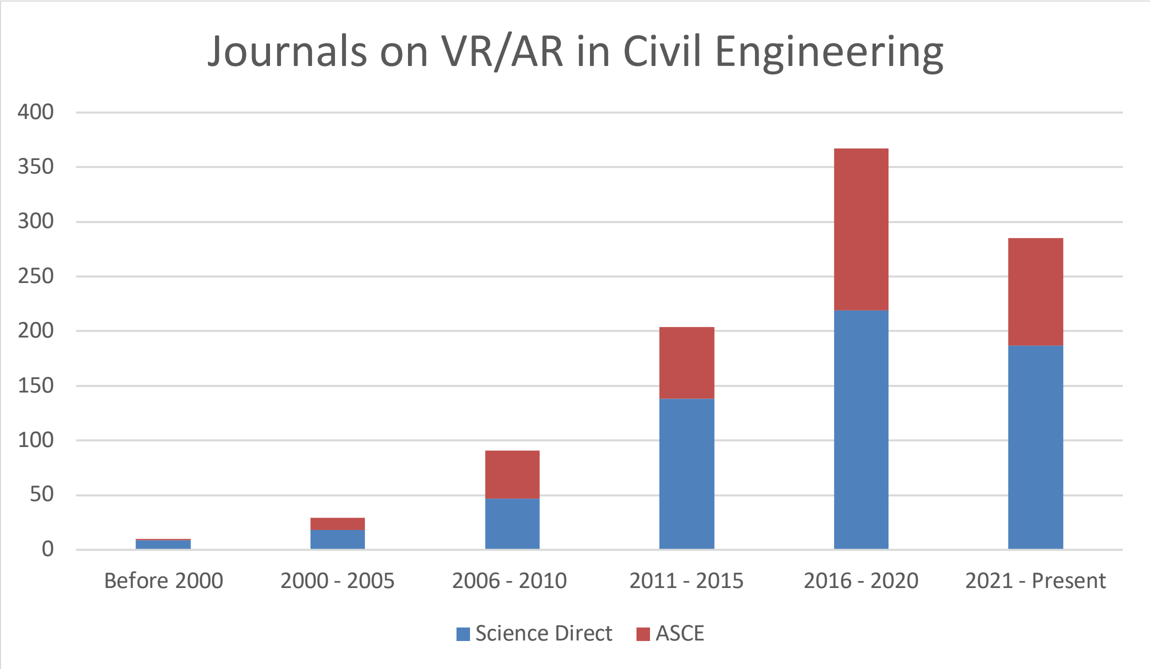

Figure 51. Number of Journals published about AR/VR in Civil Engineering

Table 1 categorizes major research and applications by time period, highlighting key publications and applications, such as aerospace simulations, architecture model visualization, engineering education, employee training, virtual design and construction, site survey, inspection, and asset management. While research and applications have been prolific, the recent years show a relative stagnation, indicating the need for continued exploration and innovation in the field.

Table 1. Major Research and Applications of AR/VR in Civil Engineering

Years	Science Direct	ASCE	Major Applications	Major Research	Major Publication
Before 2000	9	1	Aero Space Simulations		Heilig, 1960; Sutherland, 1968; Brooks Jr, 1971; Kocian, 1977; Rosenberg, 1993; Milgram et al., 1995.

2000 - 2005	18	11	Architecture Model Visualization	Mobile AR	Whyte, 2003; Regenbrecht et al., 2004; Phares et al., 2004;
2005 - 2010	47	44	Engineering education, Employee Training	Using AR to geolocate the photogrammetry points	Antony et al., 2006; Shin and Duston, 2008; Golparvar-Fard et al., 2009; Henderson, 2009; Cheng et al., 2010
2010 - 2015	138	66	Virtual Design & Construction, Site Survey and Inspection.	Occlusion, GNSS, Marker less AR.	Boton, Kubicki, & Halin, 2013; Bae, Golparvar-Fard, & White, 2014; Williams et al., 2015;
2015 - 2020	219	148	Asset Management	BIM, Point clouds, Artificial Intelligence with AR	Golparvar-Fard and Lin, 2017; Chu, Mathews, & Love 2018; Du et al., 2018; Karaaslan, Bagci, and Catbas, 2019; Wang and Piao, 2019; Dang & Shim 2019; Moreu et al., 2019
2021 - Present	187	98	Life Cycle Management	BIM, IoT, GIS, Digital Twin	Chung et al., 2021; Chalhoub et al., 2021; Schranz et al., 2021; Hasan et al., 2022; Hajirasouli et al., 2022

Despite the availability of affordable and powerful AR/VR devices, limited research on the technology's benefits hinders widespread adoption. The paper suggests avenues for future research, including the development of a framework for AR-based processes in construction, identification of occupational health and safety effects for users of headsets, life cycle cost analysis, benefit-cost analysis, and exploring applications of computer vision and machine learning with AR. Addressing these research gaps will contribute to bridging the existing divide between the theoretical potential and practical implementation of AR technology in construction.

References

Akcamete, A., X. Liu, B. Akinci, and J. H. Garrett. "Integrating and visualizing maintenance and repair work orders in BIM: Lessons learned from a prototype." In CONVR: Proceedings of the 11th International Conference on construction applications of virtual reality, 636-649. NM2011.

Alaryan, A., Beltagi, E., A. Elshahat, and M. Dawood. "Causes and Effects of Change Orders on Construction Projects in Kuwait." International Journal of Engineering Research and Applications 4, no. 7 (2014), 1-8. ISSN : 2248-9622.

Antony Chettupuzha, A. J., B. Farooq, C. Y. Shih, J. L. Wright, S. Lee, S. Kiziltas, and A. Smailagic. "Design and Evaluation of Augmented Reality Interfaces for Bridge Inspection." In Joint International Conference on Computing and Decision Making in Civil and Building Engineering, 1477-1486. Montréal, Canada2006.

Bae, H., Golparvar-Fard, M., & White, J. (2014). Rapid image-based localization using clustered 3D point cloud models with geo-location data for AEC/FM mobile augmented reality applications. Computing in Civil and Building Engineering (2014). doi:10.1061/9780784413616.105
https://doi.org/10.1061/9780784413616.105

Behzadan, A. H., S. Dong, and V. R. Kamat. "Augmented reality visualization: A review of civil infrastructure system applications." Advanced Engineering Informatics 29, no. 2 (2015), 252-267. doi:10.1016/j.aei.2015.03.005.
https://doi.org/10.1016/j.aei.2015.03.005

Bernhardt, Sylvain, Stéphane A. Nicolau, Luc Soler, and Christophe Doignon. "The status of augmented reality in laparoscopic surgery as of 2016." Medical Image Analysis 37 (2017), 66-90. doi:10.1016/j.media.2017.01.007.
https://doi.org/10.1016/j.media.2017.01.007

Boton, C., S. Kubicki, and G. Halin. "Designing adapted visualization for collaborative 4D applications." Automation in Construction 36 (2013), 152-167. doi:10.1016/j.autcon.2013.09.003.
https://doi.org/10.1016/j.autcon.2013.09.003

Brooks JR, F. P. "GROPE-I: A Computer Display to the sense of feel." In Information processing 71: Proceedings of IFIP Congress 71, organized by the International Federation for information processing, 759-763. Ljubljana, Yugoslavia: North Holland Pub. Co.,, 1971.

Burdea, G. C., and P. Coiffet. "Introduction." In Virtual reality technology, 3rd ed., 7-8. John Wiley & Sons, 2017.

Carrozzino, M., and M. Bergamasco. "Beyond virtual museums: Experiencing immersive virtual reality in real museums." Journal of Cultural Heritage 11, no. 4 (2010), 452-458. doi:10.1016/j.culher.2010.04.001.
https://doi.org/10.1016/j.culher.2010.04.001

Chalhoub, J., Ayer, S. K., & McCord, K. H. (2021). Augmented reality to enable users to identify deviations for model reconciliation. Buildings, 11(2), 77.
https://doi.org/10.3390/buildings11020077

Chalhoub, Jad, and Steven K. Ayer. "Exploring the performance of an augmented reality application for construction layout tasks." Multimedia Tools and Applications 78, no. 24 (2019), 35075-35098. doi:10.1007/s11042-019-08063-5.
https://doi.org/10.1007/s11042-019-08063-5

Chavan, S. R. "Augmented Reality vs. Virtual Reality: Differences and Similarities." International Journal of Advanced Research in Computer Engineering & Technology 5 (2016), 1947-1952.

Cheng, C., S. Leu, C. Lin, and C. Fan. "Characteristic analysis of occupational accidents at small construction enterprises." Safety Science 48, no. 6 (2010), 698-707. doi:10.1016/j.ssci.2010.02.001.

https://doi.org/10.1016/j.ssci.2010.02.001

Chi, H., S. Kang, and X. Wang. "Research trends and opportunities of augmented reality applications in architecture, engineering, and construction." Automation in Construction 33 (2013), 116-122. doi:10.1016/j.autcon.2012.12.017.
https://doi.org/10.1016/j.autcon.2012.12.017

Chu, M., J. Matthews, and P. E. Love. "Integrating mobile building information modelling and augmented reality systems: An experimental study." Automation in Construction 85 (2018), 305-316. doi:10.1016/j.autcon.2017.10.032.
https://doi.org/10.1016/j.autcon.2017.10.032

Chung, S., Cho, C. S., Song, J., Lee, K., Lee, S., & Kwon, S. (2021). Smart facility management system based on open bim and augmented reality technology. Applied Sciences, 11(21), 10283. https://doi.org/10.3390/app112110283

Dang, N., and C. Shim. "BIM-based innovative bridge maintenance system using augmented reality technology." Lecture Notes in Civil Engineering, 2019, 1217-1222. doi:10.1007/978-981-15-0802-8_195.
https://doi.org/10.1007/978-981-15-0802-8_195

Delhi, Venkata S., and Abhishek R. Singh. "User behaviour in AR-BIM-based site layout planning." International Journal of Product Lifecycle Management 11, no. 3 (2018), 221. doi:10.1504/ijplm.2018.10015947.
https://doi.org/10.1504/IJPLM.2018.10015947

Dolage, D., and D. Rathnamali. "Causes of time overrun in construction phase of building projects : A case study on Department of engineering services of Sabaragamuwa provincial council." Engineer: Journal of the Institution of Engineers, Sri Lanka 46, no. 3 (2013), 9. doi:10.4038/engineer.v46i3.6780.
https://doi.org/10.4038/engineer.v46i3.6780

Du, J., Y. Shi, Z. Zou, and D. Zhao. "CoVR: Cloud-based multiuser virtual reality headset system for project communication of remote users." Journal of Construction Engineering and Management 144, no. 2 (2018), 04017109. doi:10.1061/(asce)co.1943-7862.0001426. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001426

Du, J., Z. Zou, Y. Shi, and D. Zhao. "Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making." Automation in Construction 85 (2018), 51-64. doi:10.1016/j.autcon.2017.10.009. https://doi.org/10.1016/j.autcon.2017.10.009

Gaudiosi, J. "How virtual reality is changing the construction industry." Last modified August 25, 2015. https://fortune.com/2015/08/25/mccarthy-construction-vr/.

Gavaghan, Kate, Matteo Fusaglia, Matthias Peterhans, and Stefan Weber. "Augmented reality for laparoscopic liver surgery." Laparoscopic Liver, Pancreas, and Biliary Surgery, 2016, 47-61. doi:10.1002/9781118781166.ch4. https://doi.org/10.1002/9781118781166.ch4

Golparvar-Fard, M., S. Savarese, and F. Peña-Mora. "Interactive visual construction progress monitoring with D4AR - 4D augmented reality - Models." Construction Research Congress 2009, 2009. doi:10.1061/41020(339)5. https://doi.org/10.1061/41020(339)5

Hajirasouli, A., Banihashemi, S., Drogemuller, R., Fazeli, A., & Mohandes, S. R. (2022). Augmented reality in design and construction: Thematic analysis and conceptual frameworks. Construction Innovation, 22(3), 412-443. https://doi.org/10.1108/CI-01-2022-0007

Hasan, S. M., Lee, K., Moon, D., Kwon, S., Jinwoo, S., & Lee, S. (2022). Augmented reality and digital twin system for interaction with construction machinery. Journal of Asian Architecture and Building Engineering, 21(2), 564-574. https://doi.org/10.1080/13467581.2020.1869557

Heilig, M. L. (1960). Stereoscopic-television apparatus for individual use. U.S. Patent No. 2,955,156. Long Beach, New York: U.S. Patent and Trademark Office.

Heilig, M. L. (1962). Sensorama simulator. U.S. Patent No. 3,050,870. Washington, DC: U.S. Patent and Trademark Office.

Henderson, Steven J., and Steven Feiner. "Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret." 2009 8th IEEE International Symposium on Mixed and Augmented Reality, 2009. doi:10.1109/ismar.2009.5336486.
https://doi.org/10.1109/ISMAR.2009.5336486

Hinze, J., M. Hallowell, and K. Baud. "Construction-safety best practices and relationships to safety performance." Journal of Construction Engineering and Management 139, no. 10 (2013), 04013006. doi:10.1061/(asce)co.1943-7862.0000751.
https://doi.org/10.1061/(ASCE)CO.1943-7862.0000751

Hořejší, Petr. "Augmented Reality System for Virtual Training of Parts Assembly." Procedia Engineering 100 (2015), 699-706. doi:10.1016/j.proeng.2015.01.422.
https://doi.org/10.1016/j.proeng.2015.01.422

Karaaslan, E., U. Bagci, and F. N. Catbas. "Artificial intelligence assisted infrastructure assessment using mixed reality systems." Transportation Research Record: Journal of the Transportation Research Board 2673, no. 12 (2019), 413-424. doi:10.1177/0361198119839988.
https://doi.org/10.1177/0361198119839988

Kim, Y. T., J. Lee, S. Lee, and J. Choi. "Construction and inspection management system using mobile augmented reality." The 19th Korea-Japan Joint Workshop on Frontiers of Computer Vision, 2013. doi:10.1109/fcv.2013.6485467.
https://doi.org/10.1109/FCV.2013.6485467

Koch, C., M. Neges, M. König, and M. Abramovici. "Natural markers for augmented reality-based indoor navigation and facility maintenance." Automation in Construction 48 (2014), 18-30. doi:10.1016/j.autcon.2014.08.009.
https://doi.org/10.1016/j.autcon.2014.08.009

Koch, C., S. G. Paal, A. Rashidi, Z. Zhu, M. König, and I. Brilakis. "Achievements and Challenges in Machine Vision-Based Inspection of Large Concrete Structures." Advances in Structural Engineering 17, no. 3 (2014), 303-318. doi:10.1260/1369-4332.17.3.303.
https://doi.org/10.1260/1369-4332.17.3.303

Kocian, D. F. "A visually-coupled airborne systems simulator (VCASS)-An approach to visual simulation." In Proceedings of the 1977 United States conference of research on the shroud of Turin. Albuquerque, NM1977.

Lamb, P. "ARToolKit home page." Last modified 1999. https://www.hitl.washington.edu/artoolkit/.

LaViola Jr, Joseph J., Robert A. Sottilare, Brian M. Williamson, Conner Brooks, Sergiu Veazanchin, and Pat Garrity. "Using Augmented Reality to Tutor Military Tasks in the Wild." In Interservice/industry Training, Simulation and Education Conference: Simulation and Training : Transforming 21st Century Operations. 2015. https://gifttutoring.org/attachments/download/1414/15050.pdf.

Lee, S., and Ö. Akin. "Augmented reality-based computational fieldwork support for equipment operations and maintenance." Automation in Construction 20, no. 4 (2011), 338-352. doi:10.1016/j.autcon.2010.11.004.
https://doi.org/10.1016/j.autcon.2010.11.004

Lele, A. "Virtual reality and its military utility." Journal of Ambient Intelligence and Humanized Computing 4, no. 1 (2011), 17-26. doi:10.1007/s12652-011-0052-4.
https://doi.org/10.1007/s12652-011-0052-4

Li, W., A. Nee, and S. Ong. "A state-of-the-Art review of augmented reality in engineering analysis and simulation." Multimodal Technologies and Interaction 1, no. 3 (2017), 17. doi:10.3390/mti1030017.
https://doi.org/10.3390/mti1030017

Lin, Jacob J., and Mani Golparvar-Fard. "Proactive Construction Project Controls via Predictive Visual Data Analytics." Computing in Civil Engineering 2017, 2017. doi:10.1061/9780784480830.019.
https://doi.org/10.1061/9780784480830.019

Livingston, Mark A., Lawrence J. Rosenblum, Dennis G. Brown, Gregory S. Schmidt, Simon J. Julier, Yohan Baillot, J. E. Swan, Zhuming Ai, and Paul Maassel. "Military Applications of Augmented Reality." Handbook of Augmented Reality, 2011, 671-706. doi:10.1007/978-1-4614-0064-6_31.
https://doi.org/10.1007/978-1-4614-0064-6_31

Macedo, A. C., and I. L. Silva. "Analysis of occupational accidents in Portugal between 1992 and 2001." Safety Science 43, no. 5-6 (2005), 269-286. doi:10.1016/j.ssci.2005.06.004.
https://doi.org/10.1016/j.ssci.2005.06.004

Mao, Chia-Chi, Chung-Chong Sun, and Chien-Hsu Chen. "Evaluate Learner's Acceptance of Augmented Reality Based Military Decision Making Process Training System." Proceedings of the 5th International Conference on Information and Education Technology - ICIET '17, 2017. doi:10.1145/3029387.3029418.
https://doi.org/10.1145/3029387.3029418

Mazuryk, T., and M. Gervautz. Virtual reality: History, application, technology and future. 1996, https://www.cg.tuwien.ac.at/research/publications/1996/mazuryk-1996-VRH/TR-186-2-96-06Paper.pdf.

Vienna University of Technology, Institute of Computer Graphics

Milgram, P., H. Takemura, A. Utsumi, and F. Kishino. "Augmented reality: A class of displays on the reality-virtuality continuum." Telemanipulator and Telepresence Technologies, 1995. doi:10.1117/12.197321.
https://doi.org/10.1117/12.197321

Moore, M., Phares, B., Graybeal, B., Rolander, D., & Washer, G. (2001). Reliability of Visual Inspection for Highway Bridges, Volume 1, Final Report And, Volume II, Appendices.

Moreu, F., B. Bleck, S. Vemuganti, D. Rogers, and D. Mascrenas. "Augmented reality tools for enhanced structural inspection." Structural Health Monitoring 2017, 2017. doi:10.12783/shm2017/14221.
https://doi.org/10.12783/shm2017/14221

Moreu, F., C. Lippitt, D. Maharajan, M. Aguero, and X. Yuan. Augmented Reality Enhancing the Inspections of Transportation Infrastructure: Research, Education, and Industry Implementation. United States of America, Department of Transportation, 2019, https://digitalcommons.lsu.edu/transet_pubs/55/.

Mourtzis, Dimitris, Vasilios Zogopoulos, and Ekaterini Vlachou. "Augmented Reality supported Product Design towards Industry 4.0: a Teaching Factory paradigm." Procedia Manufacturing 23 (2018), 207-212. doi:10.1016/j.promfg.2018.04.018.
https://doi.org/10.1016/j.promfg.2018.04.018

Nagapan, S., A. R. Ismail, and A. Ade. "A review of construction waste cause factors." In Asian Conference on Real Estate (2011) . Johor, Malaysia.

Napolitano, R., Z. Liu, C. Sun, and B. Glisic. "Combination of image-based documentation and augmented reality for structural health monitoring and building pathology." Frontiers in Built Environment 5 (2019). doi:10.3389/fbuil.2019.00050.
https://doi.org/10.3389/fbuil.2019.00050

Nicolau, Stéphane, Luc Soler, Didier Mutter, and Jacques Marescaux. "Augmented reality in laparoscopic surgical oncology." Surgical Oncology 20, no. 3 (2011), 189-201. doi:10.1016/j.suronc.2011.07.002.
https://doi.org/10.1016/j.suronc.2011.07.002

Omar, T., and M. L. Nehdi. "Data acquisition technologies for construction progress tracking." Automation in Construction 70 (2016), 143-155. doi:10.1016/j.autcon.2016.06.016.
https://doi.org/10.1016/j.autcon.2016.06.016

Park, C., and H. Kim. "A framework for construction safety management and visualization system." Automation in Construction 33 (2013), 95-103. doi:10.1016/j.autcon.2012.09.012.
https://doi.org/10.1016/j.autcon.2012.09.012

Phares, B. M., Washer, G. A., Rolander, D. D., Graybeal, B. A., & Moore, M. (2004). "Routine Highway Bridge Inspection Condition Documentation Accuracy and Reliability". Journal of Bridge Engineering, 9(4), 403-413. doi:10.1061/(asce)1084-0702(2004)9:4(403)
https://doi.org/10.1061/(ASCE)1084-0702(2004)9:4(403)

Postlethwaite, D. "Community College Welding Program Update." Welding Journal, American Welding Society, 2012, 33-37.

Regenbrecht, H., T. Lum, P. Kohler, C. Ott, M. Wagner, W. Wilke, and E. Mueller. "Using augmented virtuality for remote collaboration." Presence: Teleoperators and Virtual Environments 13, no. 3 (2004), 338-354. doi:10.1162/1054746041422334.
https://doi.org/10.1162/1054746041422334

Rosenberg, L. B. "The use of virtual fixtures to enhance operator performance in time delayed teleoperation." PsycEXTRA Dataset, 1993. doi:10.1037/e477812004-001.
https://doi.org/10.1037/e477812004-001

Rubio-Tamayo, J., M. Gertrudix Barrio, and F. García García. "Immersive environments and virtual reality: Systematic review and advances in communication, interaction and

simulation." Multimodal Technologies and Interaction 1, no. 4 (2017), 21. doi:10.3390/mti1040021.
https://doi.org/10.3390/mti1040021

Sacks, R., A. Perlman, and R. Barak. "Construction safety training using immersive virtual reality." Construction Management and Economics 31, no. 9 (2013), 1005-1017. doi:10.1080/01446193.2013.828844.
https://doi.org/10.1080/01446193.2013.828844

Salamak, M., and M. Januszka. "BIM models and augmented reality for concrete bridge inspections." In 11th Central European Congress on Concrete Engineering CCC2015, 25-28. Hainburg2015.

Satava, R., and S. Jones. "Medical Applications of Virtual Reality." In Virtual and adaptive environments: Applications, implications, and human performance issues, edited by L. J. Hettinger and M. W. Haas, 325-343. Lawrence Erlbaum Associates, 2003.
https://doi.org/10.1201/9781410608888.ch15

Sawacha, E., S. Naoum, and D. Fong. "Factors affecting safety performance on construction sites." International Journal of Project Management 17, no. 5 (1999), 309-315. doi:10.1016/s0263-7863(98)00042-8.
https://doi.org/10.1016/S0263-7863(98)00042-8

Schranz, C., Urban, H., & Gerger, A. (2021). Potentials of Augmented Reality in a BIM based building submission process. Journal of Information Technology in Construction, 26.
https://doi.org/10.36680/j.itcon.2021.024

See, J. E., Drury, C. G., Speed, A., Williams, A., & Khalandi, N. (2017). "The Role of Visual Inspection in the 21st Century". In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 61(1), 262-266. https://doi.org/10.1177/1541931213601548
https://doi.org/10.1177/1541931213601548

Shin, D. H., and P. S. Dunston. "Identification of application areas for augmented reality in industrial construction based on technology suitability." Automation in Construction 17, no. 7 (2008), 882-894. doi:10.1016/j.autcon.2008.02.012.
https://doi.org/10.1016/j.autcon.2008.02.012

Sidiq, M., T. Lanker, and K. Makhdoomi. "Augmented Reality VS Virtual Reality." International Journal of Computer Science and Mobile Computing 6, no. 6 (2017), 324-327. https://www.ijcsmc.com/docs/papers/June2017/V6I6201748.pdf.

Smith, J. G. "Constructability reviews | WBDG - Whole building design guide." Last modified August 10, 2016. https://www.wbdg.org/resources/constructability-reviews.

Sood, R. "Applications of Augmented Reality." In Pro Android augmented reality, 1st ed., 1-12. Springer Science & Business, 2012.
https://doi.org/10.1007/978-1-4302-3946-8_1

Sutherland, I. E. "A head-mounted three-dimensional display." In Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, edited by Thompson, 757-764. San Francisco, CA1968.
https://doi.org/10.1145/1476589.1476686

Sutherland, I. E. "The Ultimate Display." In Information Processing,1965: Proceedings of IFIP Congress 65, organized by the international Federation for information processing. New York, NY: London: Macmillan and Co., 1965.

Tam, C., S. Zeng, and Z. Deng. "Identifying elements of poor construction safety management in China." Safety Science 42, no. 7 (2004), 569-586. doi:10.1016/j.ssci.2003.09.001.
https://doi.org/10.1016/j.ssci.2003.09.001

Tatić, D., and B. Tešić. "The application of augmented reality technologies for the improvement of occupational safety in an industrial environment." Computers in Industry 85 (2017), 1-10. doi:10.1016/j.compind.2016.11.004.
https://doi.org/10.1016/j.compind.2016.11.004

Van Krevelen, D., and R. Poelman. "A survey of augmented reality technologies, applications and limitations." International Journal of Virtual Reality 9, no. 2 (2010), 1-20. doi:10.20870/ijvr.2010.9.2.2767.
https://doi.org/10.20870/IJVR.2010.9.2.2767

VRcollab. "Redefining BIM & VDC collaboration in architecture, engineering and construction." Last modified 2019. https://vrcollab.com/.

VRTEX 360. Last modified 2013. https://www.lincolnelectric.com/en-gb/equipment/training-equipment/vrtex360/pages/vrtex-360.aspx.

Wang, Ting-Kwei, and Yanmei Piao. "Development of BIM-AR-Based Facility Risk Assessment and Maintenance System." Journal of Performance of Constructed Facilities 33, no. 6 (2019), 04019068. doi:10.1061/(asce)cf.1943-5509.0001339.
https://doi.org/10.1061/(ASCE)CF.1943-5509.0001339

Wang, X., P. E. Love, M. J. Kim, C. Park, C. Sing, and L. Hou. "A conceptual framework for integrating building information modeling with augmented reality." Automation in Construction 34 (2013), 37-44. doi:10.1016/j.autcon.2012.10.012.
https://doi.org/10.1016/j.autcon.2012.10.012

Wang, Y., & Elhag, T. M. (2008). Evidential reasoning approach for bridge condition assessment. Expert Systems with Applications, 34(1), 689-699. doi:10.1016/j.eswa.2006.10.006
https://doi.org/10.1016/j.eswa.2006.10.006

Whyte, J. "Innovation and users: Virtual reality in the construction sector." Construction Management and Economics 21, no. 6 (2003), 565-572. doi:10.1080/0144619032000113690.
https://doi.org/10.1080/0144619032000113690

William East, E., N. Nisbet, and T. Liebich. "Facility management handover model view." Journal of Computing in Civil Engineering 27, no. 1 (2013), 61-67. doi:10.1061/(asce)cp.1943-5487.0000196.

https://doi.org/10.1061/(ASCE)CP.1943-5487.0000196

Williams, G., M. Gheisari, P. Chen, and J. Irizarry. "BIM2MAR: An efficient BIM translation to mobile augmented reality applications." Journal of Management in Engineering 31, no. 1 (2015). doi:10.1061/(asce)me.1943-5479.0000315.
https://doi.org/10.1061/(ASCE)ME.1943-5479.0000315

Zaher, M., D. Greenwood, and M. Marzouk. "Mobile augmented reality applications for construction projects." Construction Innovation, 2018. doi:10.1108/ci-02-2017-0013.
https://doi.org/10.1108/CI-02-2017-0013

Zhou, Y., H. Luo, and Y. Yang. "Implementation of augmented reality for segment displacement inspection during tunneling construction." Automation in Construction 82 (2017), 112-121. doi:10.1016/j.autcon.2017.02.007.
https://doi.org/10.1016/j.autcon.2017.02.007

Zhu, W., X. Peng, and M. C. Leu. "Engineering Applications of Virtual Reality." Wiley Online Library, 2015. doi.org/10.1002/9781118985960.meh213.
https://doi.org/10.1002/9781118985960.meh213

Zhu, Z., S. German, and I. Brilakis. "Detection of large-scale concrete columns for automated bridge inspection." Automation in Construction 19, no. 8 (2010), 1047-1055. doi:10.1016/j.autcon.2010.07.016.
https://doi.org/10.1016/j.autcon.2010.07.016