Univerza *v Ljubljani*
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DHANJIT SINGER

USING AUGMENTED REALITY IN HYDROPOWER PLANT MANAGEMENT AND MAINTENANCE

MASTER THESIS

SECOND CYCLE MASTER STUDY PROGRAMME BUILDING INFORMATION MODELLING – BIM A+

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USING AUGMENTED REALITY IN HYDROPOWER PLANT MANAGEMENT AND MAINTENANCE

UPORABA RAZŠIRJENE RESNIČNOSTI ZA UPRAVLJANJE IN VZDRŽEVANJE HIDROELEKTRARN

BIM A+ European Master in Building Information Modelling

Master thesis No.:

Supervisor: Assist. Prof. Matevž Dolenc, Ph.D.

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Izvleček:

Informacijsko modeliranje zgradb (BIM) se je v zadnjem času uveljavilo, kot standarden način projektiranja gradbenih objektov – tudi hidro-energetskih, ki predstavljajo poseben izziv skozi celoten življenski cikelj, še posebej pa v fazi upravljanja in vzdrževanja. Tudi starejši hidro-energetski objekti se nadgrajujejo z najsodobnejšimi tehnologijami s ciljem zagotavljanja čiste in poceni električne energije. Razvoj tehnologij industrije 4.0 je obogočil nove priložnosti naprednejšega upravljanja s hidro-energetskimi objekti v fazi uporabe ter vzdrževanja z vključevanjem tehnologij umetne inteligence in drugih digitalnih tehnologij.

Razširjena resničnost (angl. Augmented reallity - AR) je ena izmed informacijskih tehnologij, ki odpiraja nove možnosti kognitivne pomoči uporabnikom v različnih industrijskih. Cilj raziskave je poročati in oceniti potencial in izzive uporabe razširjene resničnosti v kontekstu vzdrževanja in upravljanja hidro-energetskih objektov. Pri tem sta obravnavana dva osnovna uporabniška scenarija za uporabo razširjene resničnosti: (1) primer sodobnih hidro-energetskih objektov za katere je izdelan model BIM ter (2) starejše hidro-energetske objekte za katere model BIM ni dostopen. Raziskava je pokazala, da lahko razširjena resničnost prispeva k učikovitejšemu upravljanju in vzdrževanju obravnavanih objektov.

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Abstract:

The hydropower plants are increasingly constructed and managed on a building information modelling (BIM) platform and operations are getting automated for better performance. With the energy market getting competitive due to the technological advancements in the solar and wind power sector, even the ageing power plants are also upgraded with the latest technologies to maintain their competitiveness as cheap and clean energy. But the maintenance and inspection are still carried out manually using the conventional method of using paper-based manuals, 2D drawings and specifications.

Therefore, Augmented reality (AR) is one of the promising technologies for cognitive assistance in a complex working environment that requires manual input. The thesis focuses on the potential of AR technologies for the maintenance and inspection of power plants. It highlights the requirement and challenges to implement AR in power plants with and without 3D BIM models as the methodology is different.

The AR can facilitate the operators to better understand the task to be performed or the condition of the components by displaying the virtual information such as instructions, faulty components, analysed data and other relevant information superimposed with the real object/scene. The information can be presented in a structured way for better comprehension which would improve performance.

The introduction of new technologies to the workplace would face initial reluctance and challenges to train the workforce. The benefits would be noticed when the users are conversant with the technology.

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1 INTRODUCTION

Hydropower contributes the largest share of renewable energy in the world with almost 60 % of the renewable energy generated and accounts for about 16 % of all forms of power generated in the world as of 2020 (Beken et al., 2021). It has contributed to socioeconomic development since the late nineteenth century (Moran et al., 2018). The hydro sector has not seen major technological transformation despite being here for more than 100 years. The reluctances to the change are mainly due to unawareness of its dividends, high complexity and heterogeneity of the assets obstructing the full-scale digitalisation and lack of incentives for digital investment (Beken et al., 2021). It is estimated that half of the existing hydropower plants will require upgradation by 2030 (Agostini et al., 2020).

The ageing power plants face challenges in the market, with energy prices getting cheaper from other renewable energy sources like wind and solar, to increase the margin by maintaining the lean operation and maintenance cost and maximising the asset productivity. Digital solutions have opened up many opportunities for hydro to address the above challenges, but not many have embraced digital solutions (Beken et al., 2021). With the industrial revolution 4.0, some of the transformations to keep the operational expenses low, simpler, safer and stay competitive with other energy producers are the automation of maintenance, asset monitoring and connecting the workers (Agostini et al., 2020) by using the technologies/process such as building information modelling (BIM), augmented reality, virtual reality, mix/extended reality and digital twin.

The rapid growth of digital solutions has resulted in a positive effect on the reliability of performance and effectiveness of the activities carried out in the architecture-engineering-construction and Operation (AECO) industry.

1.1 Overview of Hydropower plant

Hydropower is the oldest source of renewable energy. Water's potential and kinetic energy rotate the generator, which produces electricity. The power generated is directly proportional to the height of the water drop (known as the head), the water discharge and the equipment efficiency. The water flows through the tunnel or penstock from the dam or weir, which pushes and rotates the turbine, and then the turbine spins the generator to produce electricity (U.S. EIA, 2022).

The power plants are of a conventional run-of-the-river/storage system or a pumped-storage system. All power plants are expected to operate at full capacity throughout their lifecycle (24/7 hours) except during maintenance and low discharge or when the energy demand is down due to cheaper energy from other sources such as solar and wind. Hydropower will play a more significant role in grid stabilisation as solar and wind power are intermittent sources and need backup supplies when their generation goes down. Therefore, hydropower will remain in the energy market until alternative sources become more viable, cheaper, cleaner and sustainable.

The new power plants are embracing the BIM platform for construction and management. The operations are automated to reduce the dependency on the workforce, thereby improving reliability and performance in the power plant operation (Beken et al., 2021). Even the operation of the older power plants is increasingly getting upgraded for automation. However, equipment maintenance still requires manual input and a trained workforce to do the job. This research focuses on improving maintenance work using digital technologies to enhance reliability and performance.

1.2 Problem statement

The hydropower plant consists of a complex system where trained personnel are required to operate and maintain equipment to keep it running. The advancement of technology in other renewable sources such as solar and wind power has brought down the cost of energy and given the stiff competition with hydro energy (Beken et al., 2021). Therefore, the digital transformation for the intelligent operation and maintenance of hydropower plants has become crucial to maintaining its competitive edge for its success.

The maintenance and inspection of hydropower plants is one of the critical activities carried out to upkeep the machine's performance and enhance the service life of the equipment. It may be done periodically based on its condition, performance monitoring (prediction) or planned interval; or repaired after its failure by in-house personnel or outsourced to qualified agency/equipment suppliers (World Bank, 2020). The machine shutdown entails enormous revenue loss to the company (owner); therefore, maintaining the components in good condition is critical to minimise the revenue losses.

The maintenance of the equipment involves manual activities, often prone to human errors causing significant damages and loss in revenue. As per CIGRE's survey (CIGRE, 2011 as cited by Yasuda & Watanabe, 2017), human errors were one of the factors leading to a major generator/equipment failure after its maintenance. The maintenance personnel leaving the foreign items/tools inside the generator compartment and incorrect connection of components/cables were the human errors causing such failure. Sometimes, the maintenance personnel are under pressure to complete the task in a given time frame which may hamper the output quality. The skill shortage in the market and the ageing of the workforce stretch the available resources, and some experts may not be available at the site to attend to critical incidents. As the hydropower company tries to optimise the resources by centralising the experts for resource sharing, the experts may be overwhelmed by work and unable to reach the site when required.

The maintenance and inspections are done using paper-based instructions, checklists, 2D drawings and manuals. Any issues outside the planned work scope have to be referred to the higher level or return to the office for the relevant manual. When the operators are less experienced, it takes more time to comprehend the task and may need to clarify the doubts from a supervisor which would reduce productivity and performance.

The digital solution would enable the operators to have a better maintenance plan and engineering decision along with the handling of an emergency, as it was the reason for the failure of the Sayano Shushenkyaya hydro plant (Acker, 2011). Augmented Reality (AR) is one of the promising digital solutions to enhance the decision-making process during the O&M period, facilitate the training of a new workforce and collaborate the experts with lesser experienced co-workers from a remote location for guidance during the maintenance/inspection of the power plants (Agostini et al., 2020).

1.3 Scope and objective

The research aims to study augmented reality (AR) technologies for the maintenance and management of hydropower plants. The following are the scope to achieve the goal:

- Review the technologies in AR and use case studies
- Identify the AR technologies suitable for the maintenance and management of hydropower plants.
- Develop a workflow and process to implement AR.

2 LITERATURE REVIEW

2.1 Building Information Modelling

Building information modelling (BIM), according to ISO 19650 part 1 (3.3.4), is the *"use of a shared digital representation of a built Asset to facilitate design, construction and operation processes to form a reliable basis for decisions*" (ISO 19650-1, 2018). It can be used for planning, designing, constructing and operating the facilities. It enables the users to visualise the scopes of the works and the issues in a simulated environment (Azhar, 2011).

The change from a conventional working process to a BIM-based process enabled the organisation to deliver a realistic and better result, increased productivity and performance, and automated the process. The evolution and innovation in the BIM process and tools have increased stakeholders' adoption of BIM in the AECO industry. The scope of digitalisation in the AECO industry is rapidly growing with innovation and technological improvement. The importance of digitalisation has gained more traction with the shift to Industry 4.0 revolution (Erboz, 2017). The collaboration and data transfer among the stakeholders involved in various phases of the project lifecycle has also improved over the years with the digitalisation process (Deng et al., 2021).

The representation of the built asset has evolved over the years from drawing boards to computer-aided 2D drawings to 3D models. The digital revolution has further enabled the incorporation of additional information over 3D models, such as time (4D), cost (5D), facility management (6D), sustainability (7D) and so on (Hamil, 2021). The information in the model is used for visualisation (rendering), fabrication/shop drawings, code review, cost estimation, activities sequencing, conflict/collision detection, forensic analysis, and operation and maintenance of facilities (Azhar, 2011).

The BIM use in the AECO industry is increasing, with many countries making it mandatory and promoting the projects to be developed on the BIM platform for its entire lifecycle stages. The use of BIM in various stages of the project lifecycle is depicted in Figure 1.

In the design and engineering stage, the BIM is essentially used for capturing existing site conditions and information such as cost, timeline, sustainability etc., in the model. The model at this stage is used for visualization, clash detection, performance analysis and communication of the model. It is used for construction quality checks, productivity and effectiveness of the proposal.

In the construction phase, the BIM is used for construction planning and visualising, progress monitoring, logistics planning and exchanging information. It is used to hand over the project to the client at the end of the construction period by having an as-built model with all the specifications and component details.

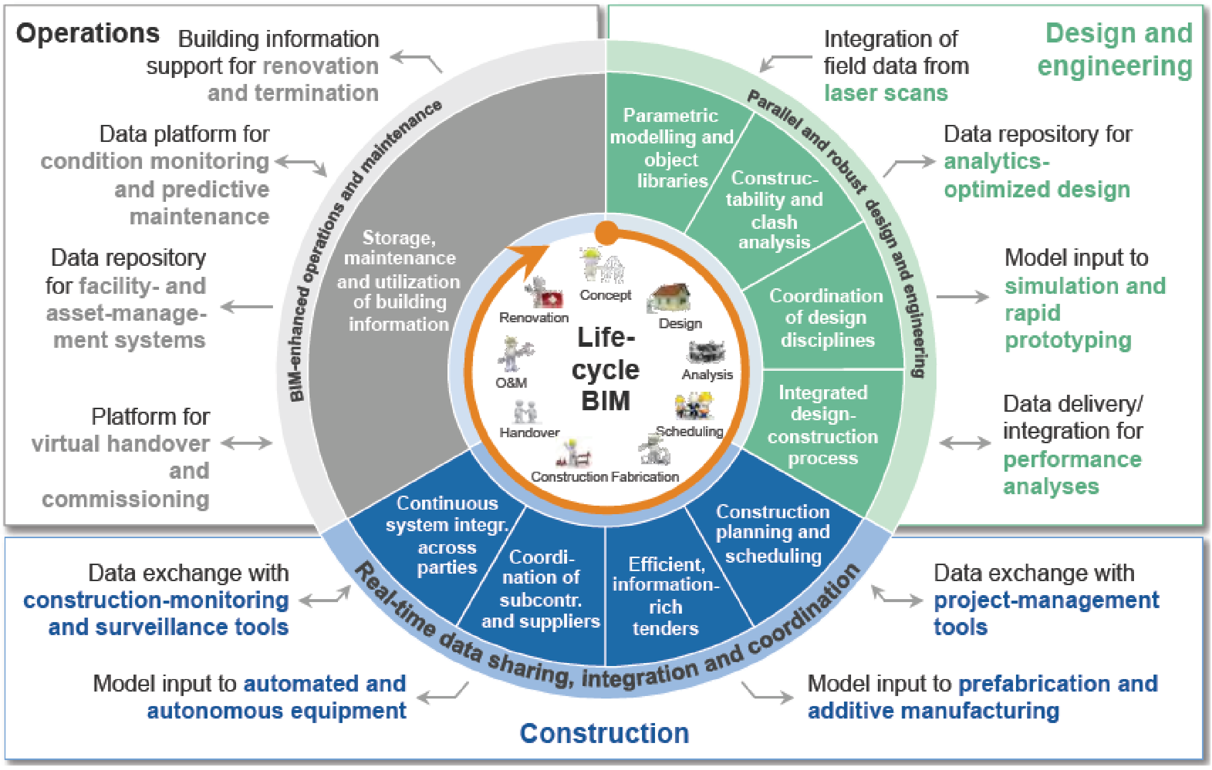

Figure 1: BIM in project lifecycle (WEF and BCG, 2016)

The operation phase of the project uses BIM for compilation of the as-built model, maintenance and management of system performances, asset management and utilization and emergency management. However, the use of BIM in the operation and maintenance of the project are found to be low even when the projects were developed using BIM in the design and construction stages (Ellis, 2022; Gao and Pishdad-Bozorgi, 2019) and the building projects with BIM-based design and construction are more popular than the other projects such as road, tunnel, bridge, hydropower etc. (Ellis, 2022). BIM plays a central data repository for the project by having 3D models and non-geometrical information, which could be used for augmented or virtual reality, digital twin etc. (Silva et al., 2021).

The key benefit of the BIM, according to CRC Construction Innovation, is *"its accurate geometrical representation of the parts of a building in an integrated data environment"* with other benefits such as better collaboration, design improvement, better control and transparency of lifecycle cost, productivity improvement, automation in the process, offers better visualisation power and lifecycle data can enable for better facilities management (CRC Construction Innovation, 2007).

As the BIM involves the collaboration of different tools, processes and people, data interoperability is the essence to capitalise on the benefits of the collaboration. The seamless sharing of model data is required among the multiple applications and disciplines involved in the different stages of the project lifecycle. Therefore, Industry Foundation Classes (IFC) is an internationally accepted open standard/protocol for seamless data sharing, which promotes the openBIM principle (buildingSMART

International, n.d.; CRC Construction Innovation, 2007). It is the vendor-neutral file format for any data exchange between various tools used to develop and operate the project.

The revolution of industry 4.0 has led to increasingly automating and digitalising the industrial process for better quality and reliability of performance. The automation and digitalisation process requires a change in methodology and technologies. Technological development has focused on digital twins (DT) in recent years (Coupry et al., 2021).

The DT is a real-time digital representation of physical objects and their systems. It uses real-time data, simulations, machine learning and reasoning algorithms to digitally represent the objects' actual conditions and environment (Deng et al., 2021; IBM, n.d.; US Department of Energy and UT-Battelle LLC, 2021). It uses the data of past and current stages to analyse and predict the future condition of the object. The digital twin concept has been widely used in various sectors, from health to manufacturing to the AECO industry, and the market is growing for the digital twin (IBM, n.d.).

The DT in operation and maintenance of the facilities are the main focus area for the researcher in the AECO industry for better quality and reliability of the asset performance as it is one of the largest parts of the project lifecycle (Coupry et al., 2021). DT enables the operators to understand the asset at the individual parts of the equipment. With the advent of the internet-of-things (IoT), it has become easier to connect all the parts with sensors for performance evaluation and decision-making (DeLuca, 2021). The BIM model is made digitally identical to its physical objects where the data from sensors are linked to the model, and the model changes the status dynamically and represents the real-time condition of the physical objects. According to DeLuca(2021), the implementation of DT would need a reliable source of data, connectivity of sensors/access to real-time data, and a system to collect data using IoTs and analysis the data.

2.1.1 BIM in Hydropower Sector

The first hydropower plant was developed in the 1880s, and many more have been constructed over the years as it is one of the cheap and clean energy sources. The hydro sector has not seen major technological transformation despite being here for ages. The reluctances to the change are mainly due to unawareness of its dividends, high complexity and heterogeneity of the assets obstructing the full-scale digitalisation and lack of incentives for digital investment (Beken et al., 2021). The project is unique and complex and takes a longer period for planning and construction (Oud, 2002).

The implementation of BIM-based hydropower projects has increased in recent years to manage the project complexity, variability and uncertainty in hydropower engineering, which helps to manage the risk, information and resources. However, the BIM use was mostly limited to the design and construction phase (West and Liu, 2021), whereas the project's life is over 50-100 years. Therefore, using digital solutions for the entire project lifecycle would give the advantage over the conventional method of development.

In the planning and design stage, BIM can be used for mapping 3D terrain modelling, sub-surface modelling, 3D collaborative design, costing and scheduling, visualisation, and clash decisions. The simulation of construction activities and coordination among various professionals, construction stage information repository, construction safety control and progress tracking (Ye et al., 2022). Mjåvatn dam in Norway was designed and constructed from 2015-2021 on a fully integrated BIM platform instead of traditional drawing. It was used for information exchange and collaboration, design optimisation and building process (Bergsager, n.d.). Smisto project, another in Norway, was also developed on the BIM platform from the conceptual planning stage to the completion stage. The team used the BIM platform to share the information digitally, and it claims to be one of the success stories in the construction of hydropower projects without issuing traditional 2D drawings (Multiconsult Group, 2016). The above-cited projects, HE Brežice and HE Mokrice in Slovenia (Starc et al., 2020), are some of the examples of hydropower projects where BIM was used for design and construction.

The BIM is used to visualise the operation and maintenance of the electromechanical and hydromechanical equipment during the operation stage, storing information such as specifications, manuals, blueprints, etc. (Ye et al., 2022). The effective operation and timely maintenance and upgradation of the plant are essential to enhance the machine performance and service life to the optimum level. With the estimate that half of the existing power plants require upgradation by 2030 (Agostini et al., 2020) and the challenge of maintaining the competitive edge for the energy cost among other energy sources such as wind and solar (Beken et al., 2021), the transformation of operation and maintenance of the hydropower plants have become crucial.

2.1.2 BIM for operation and maintenance

The operation phase of the project lifecycle is the longest period of the project life which spans up to 100 years, accounting for about 80% of the lifecycle cost (Durdyev et al., 2022). It has to be upgraded and maintained over the lifecycle with technological changes to enhance the service life and performance of the equipment at a lower cost to the owner.

The use of BIM in the hydropower sector or any other project is gaining importance due to its inherent advantage in dealing with a complex project like hydro, where many engineering disciplines and stakeholders need to collaborate to complete the work. BIM enhances the operation and maintenance of facilities by providing a virtual model and functioning as an information repository developed during earlier phases. It could be supplemented or refined during the O&M phases, where the operation and maintenance data can be stored in the model (Gerbert et al., 2016). The data from O&M can be used for predicting the maintenance requirement, performance improvement and enhancing the asset life. BIM can also be used to control and monitor the process and visualise the condition, maintenance of the components and many more. It is the single source of information for as-built models, specifications, maintenance manuals and blueprints (Durdyev et al., 2022). However, as per Durdyev et al. (2022), it comes with a challenge as not many projects were designed and constructed using BIM, and the upfront cost for the systems and resource training to start BIM in facility management is high. Even the projects developed in BIM don't continue BIM for facility management. As per the research by Ellis (2022) and Pishdad-Bozorgi (2019), BIM is used mostly for the design and construction phase of hydropower plants or any other projects and is not taken further for the operation and maintenance of the plant (Ellis, 2022; Gao and Pishdad-Bozorgi, 2019).

While the recently constructed or upgraded power plants are developed on the BIM platform and are automated using the supervisory control and data acquisition (SCADA) system, the development of DT to link the BIM model with sensory data has further enhanced the intelligence level of the system which can analyse and predict the performance, enhancing greater flexibility for operation and maintenance of the assets. The SCADA collects real-time data and has the potential to predict failures using machine learning and artificial intelligence (Devasia, 2020; Lildballe and Guldager, n.d.).

The operation of hydropower records many data, such as vibration, temperature, and pressure data, along with the power generation information. These data are collected using sensors recorded locally or in a centralised system using SCADA, and the operator sometimes takes the reading from sensors. The increased production of variable renewable energy such as solar and wind has pushed hydropower operations into a complex and demanding situation where it needs to provide grid reliability and resiliency. The variable baseload contribution to be made by the hydropower plant has to be smartly managed using technologies and advancements in sensors, data and control systems, data analytics, simulations and optimisation. Therefore, the DT is the latest development to manage the complexity of the hydropower operation. It also can predict the status of the equipment parts based on the historical operation parameters and conditions (US Department of Energy and UT-Battelle LLC, 2021). The DT has significant computing efficiency, which gives higher productivity at a minimum cost (Beken et al., 2021).

However, implementing the DT in old assets would require a detailed asset blueprint, and few assets/projects have the blueprints. Many existing power plants may not have a digital blueprint, and it would be expensive to digitalise for simulation and visualisation. The interoperability of the equipment and sensors when it is from multiple manufacturers also hampers the rate of development of DT (Devasia, 2020).

2.2 Augmented reality

The idea of augmented reality and virtual reality (VR) technology came into existence in the 1960s after the invention of the first head-mounted displays (HMD) by Ivan Sutherland. The early-stage AR use and research were focused mostly in military and government research labs; for example, the display was mounted over the helmet to select the target and night vision by military personnel. The advancement of technology has expanded its usage to other sectors like manufacturing, medical, tourism, training, entertainment and the AECO industry (Behringer, 2001). According to Caudell and Mizell, as cited by Behringer (2001), the first large-scale testing of AR systems was in the 1990s for assembling wire bundles by the Boeing factory. The challenges faced with AR technology in the early days were with the view tracking (registration /alignment of the object-based) on user's line of sight, and orientation, including camera angle as stated by Behringer, and the system was bulky due to hardware, batteries, tracking sensors and display systems (Billinghurst et al., 2014). The tracking of the object for the user while moving was experiencing a lag in information transmission.

With technological advancement, software and hardware are becoming easily accessible, and even non-programmers can build AR applications (Billinghurst et al., 2014).

According to Milgram & Kishino (1994) and Behringer (2001), augmented reality (AR) is referred to as the augmentation or enhancement of real environment information using virtual (computer graphics) information. The virtual information can be images, real-time videos, sound, text, 2D/3D models or any other information which complements each other for better perception and experiences. The technology can be known as AR systems when it combines real and virtual information; the information should be interactive in real-time and registered in 3D (Azuma, 1997). The AR system increases the user's perception and interaction with the real world by combining the virtual environment with real-world information, supporting the interaction of real information with virtual information. The information shown has 3D coordinates or references (Billinghurst et al., 2014).

The virtuality continuum, defined by Milgram & Kishino (1994), is a scale of transition between the virtual and real environments, often called mixed reality (MR). Depending on the user environment, augmented, mixed and virtual reality is defined.

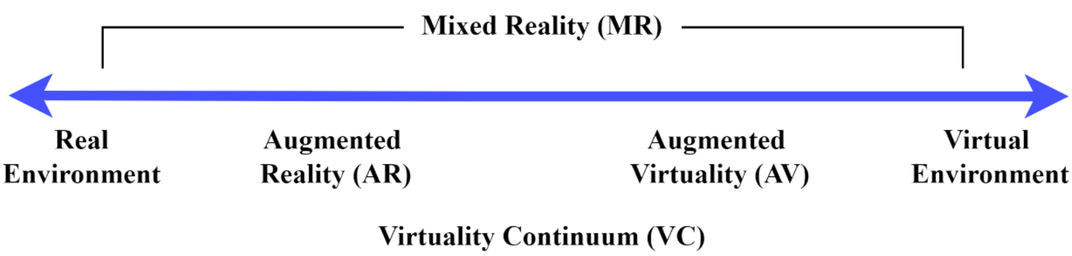

Figure 2: Representation of virtuality continuum (Milgram and Kishino, 1994).

Virtual reality (VR) is a technology which creates a fully immersive digital environment where the real world or physical environment is missing from the view (Tremosa, 2022). The user can only see the digital version of the object and its environment. Similar to AR, VR enables collaboration, planning, and visualisation of data and 3D models for better communication and coordination among the stakeholders but in a virtual environment (Schiavi et al., 2021).

Mixed reality (MR) is a technology which superimposes the digital content with the real-world environment and enables interaction with the contents. The user can interact with both digital content and real-world objects (Tremosa, 2022).

Extended reality (XR) is often referred to as an umbrella for any technology which alters the reality, including the digital content, to the real world environment. It includes AR, VR, MR and other technologies inside the virtuality continuum (Tremosa, 2022). The extent of change in user perception (immersive experience) and capabilities for interaction defines the technologies based on the virtuality continuum framework.

The following section describes AR components and their workings.

2.2.1 Components of AR

The main components of an AR system are hardware, software and user interface. The hardware consists of the processor, sensors, and input and display devices. The display device can be a head-mounted display (HMD), handheld devices such as smartphones & tablets or smart glasses. The smartphones or tablets of the current generation have all the supporting functionalities required for hardware, such as a compass, accelerometer, camera and gyroscope for the input device, display system, processors and sufficient processing capacity even with readily available smartphones.

The software is required to process the information that needs to be displayed based on the input data. It overlays the virtual information over the real-time information as requested by the user. The user interface enables the visualization of the processed information through the display devices.

2.2.2 Tracking method of AR

One of the characteristics of an AR system, according to Azuma (1997), is the virtual content is *"registered in 3D"* which gives the system the ability to track and superimpose the virtual content with the real-world environment. The system registers the initial orientation and position of the viewer regarding some know reference/anchor system known as the registration phase. It then updates the viewer's location based on the previous position, known as the tracking phase. The anchor system may be of physical objects or a virtual location defined by coordinates or dead-reckoning using inertial tracking (Billinghurst et al., 2014).

Several tracking technologies are used for registration and tracking the user's view. As per the survey on AR carried out by Billinghurst et al. (2014), several technologies have been developed over the years, and each one has special features over others based on the environment used.

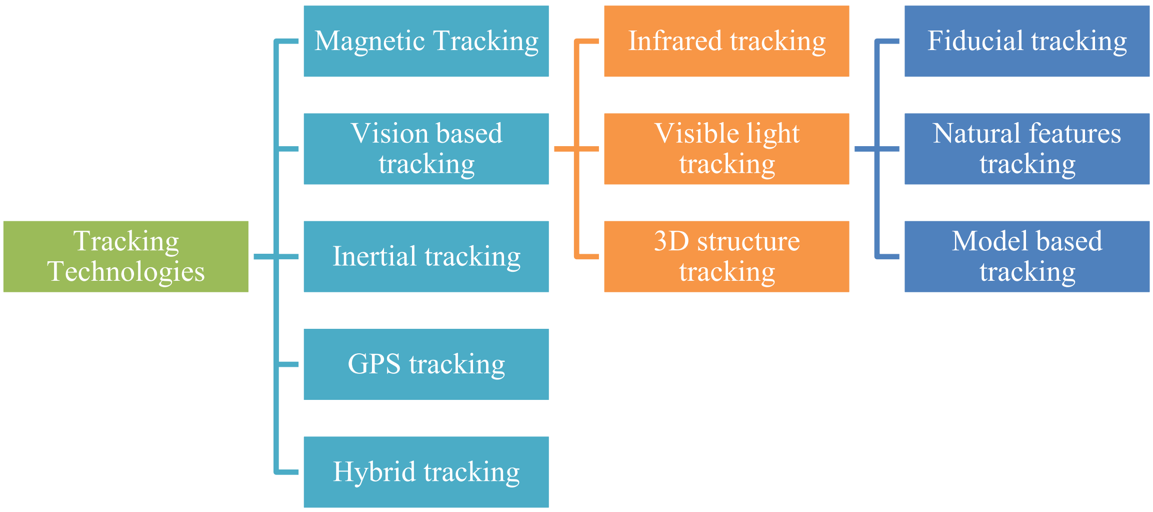

Figure 3: Tracking technologies (Billinghurst et al., 2014).

Magnetic Tracking uses the magnetic tracker as a reference system to anchor the virtual content to real-world objects. The transmitter produces an alternating magnetic field detected by the receiver. The orientation and position of the receiver can be determined by knowing the magnetic field direction and can be computed at high speed. The magnetic tracker is known for high update rates and doesn't get influenced by occlusion and optical disturbances. It is small and lightweight, but the magnetic field's strength reduces with the increased distance between the receiver and transmitter. It is prone to measurement jitter and is sensitive to other magnetic materials. It is generally used in manufacturing, medicine and maintenance (Billinghurst et al., 2014).

Vision-based tracking is the registration and tracking of the virtual content based on the camera pose, which is done using optical sensors. In their survey, Billinghurst et al. (2014) defined the vision-based tracking technologies into three methods: ***infrared tracking, visible light tracking and 3D structure sensors***. It has become popular tracking technology in recent times due to the advancement of technology in smartphones, tablets and other handheld devices, which has both camera and display screen (Billinghurst et al., 2014).

Infrared Tracking uses the targets that emit or reflect the bright light, making it easier to detect than the surrounding environment. The targets emitting the light resolve the illumination issues while using it in areas with poor lights. Light-emitting targets need power and synchronization using light sources, which is the major disadvantage of this kind of technology. This system is complex, expensive and requires the setting up of physical infrastructure to fix the targets though it is precise and scalable (Billinghurst et al., 2014).

Visible light tracking is the most common type of optical sensor tracking system, which uses cameras as it is commonly found in most devices such as phones, tablets and laptops of the current generation. The camera can be used to show the background of the real-world environment and for the initial registration of the virtual content. This type of tracking method is further categorised as *fiducial, natural feature, and model-based* (Billinghurst et al., 2014).

- *Fiducial tracking* uses an artificial marker attached to the surrounding objects/space for registration and tracking. By placing enough markers on the environment which could be detected in the scene, the position and orientation of the camera (user view) are determined. It can potentially extend the program by introducing the additional markers at a later stage. The fiducial markers have evolved from using single colour-coded basic shapes to multi-ring of multiple colours to allow longer range detection. It further evolved to the requirement of at least four known points as a reference in the environment, which is fulfilled by the corners of a simple quadrilateral shape and the additional information is encoded inside the quadrilateral. Several tools were developed to create artificial markers, such as ARTag, ARToolkitPlus (upgradation of ARToolkit) and Studierstube ES (Billinghurst et al., 2014). Examples of fiducial markers are circular/rectangular-shaped drawings on paper, QR codes, line codes, bar codes, etc. However, many markers are required to be fixed in the work environment, and the 3D position must be measured before implementing the AR (Ishii et al., 2007).
- *Natural feature tracking* uses the natural features of the environment, such as exit signage, paintings on the walls, trademarks on the components, etc., which already existed in the area (Koch et al., 2014). It is used when fiducial markers are not feasible due to size and space constraints. The unique natural features are encoded with additional information and descriptions. The camera orientation and position are computed using a similar algorithm used in fiducial tracking techniques. The most notable algorithm for natural feature detection and description are binary robust invariant scalable keypoints (BRISK) and fast retina keypoint (FREAK) (Billinghurst et al., 2014).
- *Model-based tracking* is tracking real-world objects using known 3D virtual objects such as the BIM model. The edge filters in the algorithm extract the information (shapes, size etc.) of the object detected in the real-world scene to match with the virtual object for registration and tracking (Koch et al., 2014). The method has evolved to use the virtual model with texture information and keyframes to handle complex and variable environments. One of the major innovations in tracking techniques in the unknown environment is a feature capable of creating and updating the virtual environment and simultaneously tracking the camera pose, known as Simultaneous localisation and map building (SLAM) (Bajpai and Amir-Mohammadian, 2021; Billinghurst et al., 2014). The SLAM was originally developed for robot navigation in unknown environments but was also

adopted for AR tracking. SLAM was further optimised, specifically designed for AR, and known as parallel tracking and mapping (PTAM), where the tracking using a camera and mapping of the scene were separated (Klein and Murray, 2007). Other methods based on SLAM are large-scale direct monocular SLAM (Engel et al., 2014) and Oriented-FAST and Rotated-BRIEF SLAM (Mur-Artal et al., 2015). These methods were evolved for better accuracy for tracking and higher performance than SLAM (Billinghurst et al., 2014).

3D structure tracking has evolved with the reduction in cost for sensors that can detect 3D structure information from the scene and the introduction of Microsoft Kinect. The sensor uses structured light or time-of-flight to extract 3D information of scanned points in the scene. It can extract depth information from the scene, which can be used for tracking and mapping the real-world scene. The technology, based on the extraction of 3D structure information for AR developed by Microsoft, is known as a KinectFusion system. It uses structured light depth sensors to model the 3D virtual environment from the real environment, which can be used for tracking (Billinghurst et al., 2014; Murhij and Serebrenny, 2020).

Inertial tracking uses the inertial measurement unit (IMU) sensors, gyroscopes, accelerometers and magnetometers to compute the relative position, orientations and velocity of the object. These techniques allow the measurement of orientation relative to gravity, and the shift in position is computed using inertial velocity and the time interval between each update by the tracker. The advantages of an inertial tracker are "no range limitation, no line-of-sight required, and no risk of interferences from any magnetic, acoustic, optical sources with flexibility in sampling rates, relatively higher bandwidth motion measurement with negligible latency" as cited by Billinghurst et al., (2014). However, it is susceptible to drifting of position and orientation over time, leading to errors in a position measurement. Therefore, it is combined with other tracking methodologies to correct the error (Billinghurst et al., 2014).

GPS tracking uses the Global positioning system (GPS) technology for outdoor environments. The position and orientation accuracy vary with the satellite signal coverage (deep gorge, thick forest and surroundings with tall buildings block the line of sight to the satellite). The accuracy is currently improving with the advancement of technologies and has the potential to achieve accuracy at a centimetre level with GPS enhancement technologies such as real-time kinematics (RTK). Therefore, it is used only where the accurate position and orientation are less important or combined with other tracking systems, as in hybrid tracking (Billinghurst et al., 2014).

Hybrid tracking is a combination of sensors and other tracking methods mentioned previously to improve the accuracy of tracking the position and orientation by overcoming the weakness of the individual tracker. Several tracking technologies must be combined as some tracking technology alone is insufficient for a robust solution (Zhou et al., 2008). For example, combining visual-based tracking with magnetic and inertial trackers can extend the tracking range as the latter doesn't need a line of sight.

The many mobile devices such as smartphones and tablets of the current generation have cameras, accelerators, gyroscopes, GPS and wireless networking, which can be combined to give high accuracy of position and orientation tracking for indoor and outdoor environments (Billinghurst et al., 2014). Therefore, hybrid tracking is increasingly used in AR technologies for their robustness and tracking accuracy. Site preparation is less for hybrid tracking as fewer markers will be pasted around the maintenance area (Ishii et al., 2007).

According to Bajura M and Neumann U as cited by Silva et al. (2021), the limitations of AR in the AECO industry for daily usage are the nonalignment of the tracking coordinate system with the coordinate work system and the mapping of view from the virtual camera not representing the real world camera due to incorrect position of a virtual camera.

2.2.3 AR display technologies

The real and virtual information/data are combined and displayed to the user/viewer in various display types. The two categories of AR display technology are based on the type of combination technology used and where the display takes place (Billinghurst et al., 2014). These technologies enable the superimposing of real and virtual data accurately.

Display technology based on a combination of real and virtual data: The number of procedures have to be carried out to combine the real and virtual information for the AR visualisation, which are camera calibration, registration, tracking and composition (Billinghurst et al., 2014).

Camera calibration is the process of aligning the computer-generated virtual scene to the view of the real-world scene by matching the internal and external parameters of the virtual camera with the physical camera. Internal parameters play a role in projecting a 3D scene into a 2D image. The internal parameters are computed by matching the known 3D geometric features of a set of pictures and their projection on the 2D image. The external parameters define the camera position and orientation in a known coordinate frame. It is computed by tracking the position and orientation of the physical camera. For the static scene, only the position and orientation of the physical camera are calculated. For a dynamic scene, the position and orientation of both the camera and object must be computed (Billinghurst et al., 2014).

Registration matches the coordinate frame used for rendering the virtual object/scene with the tracking coordinate frame in the real environment. The tracking coordinate frame is set by the tracking system as a coordinate reference frame to determine the position and orientation of the object or camera. It aligns the virtual scene with a real-world scene (Billinghurst et al., 2014).

The virtual scene images are generated based on each update by the tracking system after it completes the calibration and registration processes. The composition of the virtual and real-world scene can be done both digitally and physically (optically) based on the AR display system, and it is categorised into video-based, optical see-through, projection onto a physical surface/object and eye multiplexed (Billinghurst et al., 2014):

Video-based AR Display uses a video camera system to digitise the live video of the real world to combine with virtual images/scenes. The camera may be attached behind the display system to capture the real-world environment, which can be seen through the display and known as "video see-through". The structure of the video-based display is shown in Figure 4.

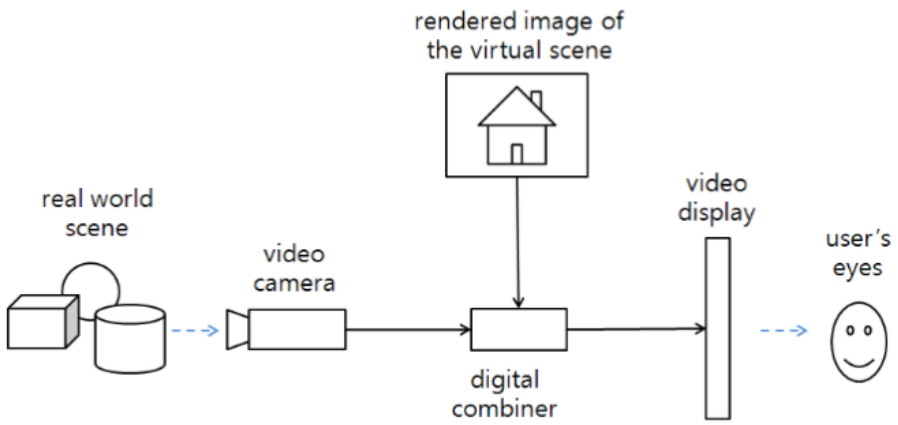

Figure 4: Structure of video-based AR display (Billinghurst et al., 2014)

This technology is the most widely used as the hardware and tools are easily available. Smartphones, tablets and PC/Laptops with webcams are the popular devices for it. It has the advantage of being accurate in controlling the process of combining real and virtual images/scenes. One of the common issues of combining the real world and virtual images is incorrect occlusion while overlaying the virtual image on the real world view, which a video-based display can easily resolve by acquiring the depth information of the real world and matching it with the depth data of virtual images. The difference in lighting and colour space of the virtual and real-world scene can also be corrected during the image combination (Billinghurst et al., 2014).

However, the user will not get a direct view of the real-world scene as the user is offered a processed video of the real-world scene. It has limitations with resolution, distortion, delay and eye displacement. The techniques to address the issues are the usage of higher resolution devices, faster update rate and algorithm for correcting the distortion while rendering. The video-based display needs more computing power for combining real and virtual images than other image-combining technologies (Billinghurst et al., 2014).

Optical see-through AR Display uses an optical system to combine virtual images with a real-world view. The real-world view seen through the optical system called beam splitters (half mirror or prisms) is combined with the reflection of a virtual image from the video display. The see-through optical structure is shown in Figure 5. With the recent development in optical technologies, transparent flat panel displays are also investigated for combining virtual and real-world scenes. This is another type of optical see-through display technology where the virtual images are projected with a semi-transparent display. The real-world scene behind the display can also be seen through it (Billinghurst et al., 2014).

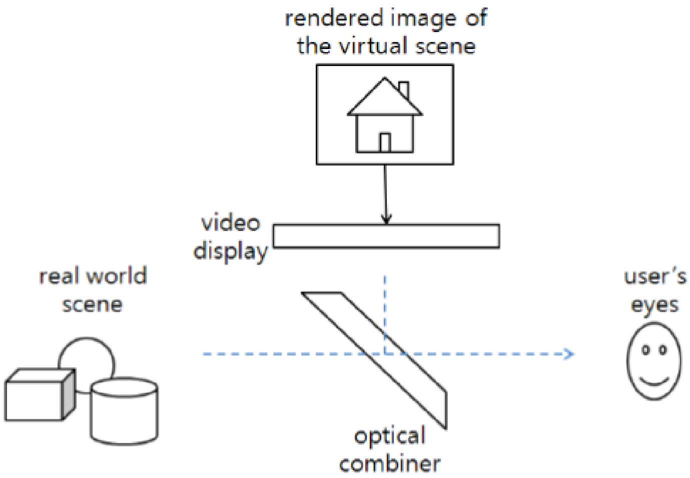

Figure 5: Structure for optical see-through AR display (Billinghurst et al., 2014)

The optical see-through display provides the user with a direct view of the real-world scene, free from limitations such as resolution, lens distortion, displacement and delays. The system is less complex and requires lesser processing power as the combination of the images is done physically. The issue is the lower accuracy for registration of the virtual image and real view scene. It requires manual calibration of the scene, which often gives a poor quality of registration of images. Temporal delay in tracking the real-world images and computation of the virtual image view based on the real-world scene for the display is another issue for the dynamic real-world scene. The change in the lighting condition of the real-world scene also affects the quality of the display's brightness (Billinghurst et al., 2014).

Projection-based AR Display projects the virtual image or scene over the real-world surface of the object of interest, such as the building/wall model. It can provide interactive augmentation of virtual images. The normal practice is to mount the projector on a wall or ceiling, which limits its usage with a fixed area for mounting. However, there have been efforts to make it mobile by miniaturising the display devices. Handheld projectors are improving, and they can be used anywhere with vision-based tracking to address mobility issues (Kim et al., 2018). This method is limited to the indoors or nearby real-world surfaces because the projection of the scene to the real-world object surface at a distance is not possible. It is not suitable for outdoor surfaces as the display is sensitive to the lighting condition and affects by shadow (Billinghurst et al., 2014).

Eye multiplexed AR Display uses the user's mind to combine the real-world view and the virtual scene. The structure of the view is shown in Figure 6. The virtual scene is registered to the physical environment, and the user combines the images in their mind. The virtual scene is displayed closer to the user's eye to appear closer to the real-world scene. The display doesn't need digital composition of the real and virtual images, which gives a direct view of the real world. The lower processing powered system is sufficient to handle the display; however, the user's mental efforts are required to match the virtual and real-world images, and the visualisation is less intuitive (Billinghurst et al., 2014).

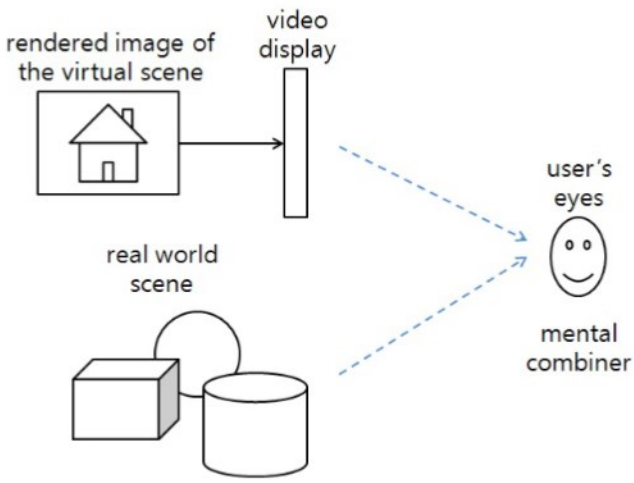

Figure 6: Structure of Eye Multiplexed display (Billinghurst et al., 2014)

Display technology based on the location of view: The AR display technology can also be categorised based on the location of the display, and it is called the "Eye-to-World spectrum". The different categories of display based on the location of view are head-attached displays, handheld and body-attached displays, and spatial displays (Billinghurst et al., 2014).

Head-attached displays present the virtual images close to the user's eye, and no physical objects obstruct the virtual images giving an occlusion-free view. The head-attached display can be a helmet or goggles of lightweight. Head-mounted displays (HMD) are the most common for AR research. The technological advancement has led to the development of smart glasses such as Google Glass, Oculus Quest 2 and Microsoft HoloLens 2 and actively researching their use in the industry. Some of the research with this method is on the direct projection of the virtual image onto the retina of the user's eye (Billinghurst et al., 2014).

Figure 7: Microsoft HoloLens 2 (Draper, 2018)

Handheld and Body attached displays are either attached to a user's body or held on hands. Though the Head-attached display gives high mobility and a better immersive experience, it has the limitation of wearability, especially in small spaces, and safety issues. Therefore, handheld and body-attached displays are mobile and can share the view with others. Even it is more socially accepted than head-attached displays. With the development of mobile technologies, smartphones and other portable devices are powerful enough to compute the AR visualisation and display of information. It comes with a camera, graphics processors and various other sensors. The most common type is handheld video-based display configuration, such as an AR system using smartphones and tablets. The optical see-through is also in the development phase. Micro projectors are another type of video-based mobile device for AR display, and there is also research on wearable devices that can be put on the chest, shoulder or wrist (Billinghurst et al., 2014).

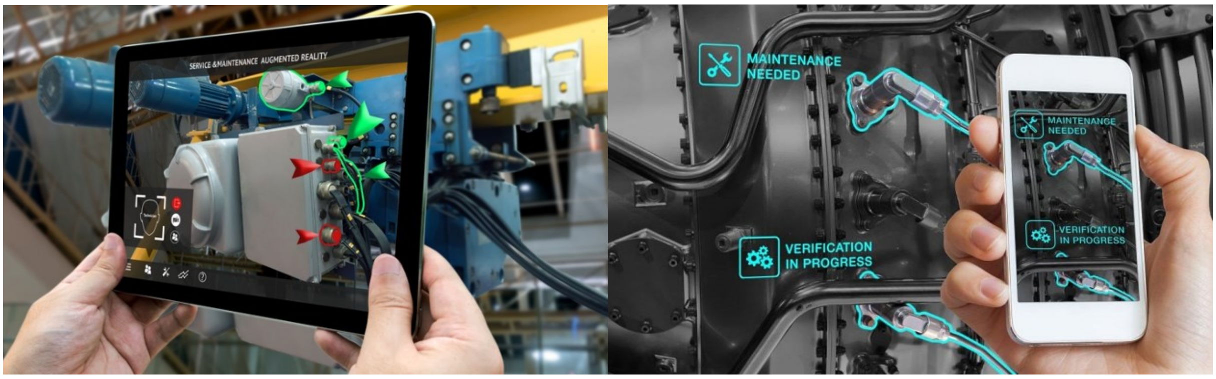

Figure 8: Handheld device: Tablet (Left- Staff Writer, 2019) & Phone (Right-Caggia, 2021)

The spatial display provides a large image view, and it's more suitable for public displays where many users share the view. It is usually fixed to a location with limitations on mobility. A typical example is using a beam splitter (half mirror) to create an optical see-through view. With the recent development of transparent LCDs and OLEDs, wide adoption and application are expected for AR display. The holographic projection film is a spatial display method where the user can see both project and real-world scenes/surfaces which uses the transparent screen (Billinghurst et al., 2014).

2.2.4 AR development tools

There are numerous software libraries and tools for the development of AR systems. Some use computer vision-based tracking, which can be used indoors, while other use sensors on the devices and is suitable for outdoor use. The various types of tools are tabulated in Table 1 along with skills and examples of tools as summarised by Billinghurst et al. (2014).

Table 1: AR tool hierarchy from the most complex to least complex (Billinghurst et al., 2014).

Type of Tool	Skill Required	Example
Low-level software library/framework	Strong programming/coding ability	ARToolkit, osgART, Studierstube, MXR-ToolKit
Rapid prototyping tools	Some programming ability, but design/prototyping skills	FLARManager, Processing, OpenFrame-works
Plug-in for existing developer tool	Skill with the developer tool that the plug-in works with	DART, AR-Mediaplug-ins, Vuforia and Metaio Unity plugins
Stand-alone AR authoring tools	No programming ability, but can learn stand-alone tool	BuildAR, Metaio Creator, Layar Creator, Wikitude Studio

The low-level software libraries and framework has the most flexibility for the development of AR but requires programming skills. The stand-alone authoring tools are the simplest tool to be used by even the user with no skills in programming, but each software has its limitations (Billinghurst et al., 2014). The technologies used by the software are changing over the year to address the limitation.

2.2.5 AR interaction technologies

AR system uses various types of input methods for interaction between the user and the system, such as a mouse, keyboard, touch screen, handheld wands, speech, gestures, etc. and are generally categorised as: "*Information browsers, 3D user interfaces, tangible user interfaces, natural user interfaces*" as given by Billinghurst et al., (2014).

Information browsers use AR display as a window to information space, and the user has to operate the window to extract the information. It uses the most basic task of AR: viewing an AR scene and browsing the given information in the window. The system visualises the virtual scene registered to the real-world space and does not need an additional navigation interface. It is one of the widely used interaction methods due to its simplicity and easier learning as it is similar to the mobile interface. However, it has limitations in interacting with virtual objects as it utilises 2D information (Billinghurst et al., 2014).

3D user interfaces support the interaction with virtual objects using various 3D user interface techniques. The 3D user interfaces are used for navigation, selecting and manipulating virtual objects. While the navigation is achieved by user movement, tracking the user's hands in 3D space and picking up the virtual blocks are an example of selection and manipulation in a 3D interface. The devices include 3D mouse or wand, 6-degree freedom joystick, Spaceballs, 3D motion tracking sensors, etc. They are used for 3D user interfaces (Billinghurst et al., 2014).

Tangible user interface uses physical objects to represent virtual objects and information and also bridges the physical world with the digital world. It limits display capabilities though it gives a natural and intuitive interaction experience. The projection of virtual objects and information on the real physical surface has a gap between interaction and presentation space (Billinghurst et al., 2014). The interaction with virtual objects is done by manipulating the physical objects, and it uses computer vision-based tracking. The drawback of the method is its requirement of physical objects for interaction, which may not be applicable for mobile and wearable applications (Billinghurst et al., 2014).

Natural user interfaces use computing power to recognise the user's motion and gestures in real-time without any sensors, unlike the 3D user interface, which uses various sensors to track the user's motions. The accuracy of the motion and gestures has improved with the depth camera introduction and technical advances in the market (Billinghurst et al., 2014). The use of gesture-based manipulation and communication of the information in AR are being studied using deep learning and artificial intelligence (Murhij and Serebrenny, 2020).

Multimodel interaction is the combination of the above interaction method to enhance the application's interactivity. The research is focused on combining various methods for better results. Some combinations are the hand gesture with speech recognition and hand gesture with the physical wand (Billinghurst et al., 2014).

2.3 AR in AECO Industry

The most potential area in the AECO industry where AR can be implemented based on the survey carried out by Meža et al. (2015) is given in Figure 9.

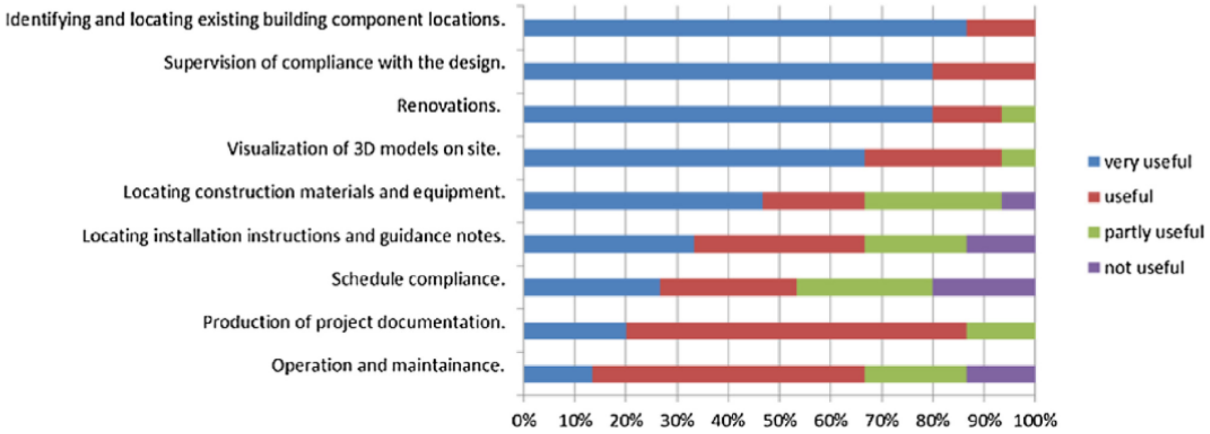

Figure 9: A most promising area for AR (Meža et al., 2015).

AR in BIM-based projects enhances the visualisation power of the user by augmenting the real environment (Silva et al., 2021), enabling better decision and coordination. It could be used from the initial project planning and design phase till the facility management phase of the assets.

According to Konstantinidis et al. (2020), the increase in the cyber-physical production system will significantly reduce human involvement in the production line operation. However, the maintenance of the assets will still require human intervention. Therefore, in the age of industry revolution 4.0, the operators need the support of connected tools and intelligent systems to perform their activities efficiently. Such tools and systems enable them to work without knowing each component's accurate locations and specifications (Konstantinidis et al., 2020).

The conventional method of maintenance involves the operator following the paper-based technical drawings and manuals for the maintenance activities, and when the major maintenance or in an emergency case, the original equipment manufacturers' (OEMs) expertise is often required, leading to production halt till the experts reach the site. As maintenance is one of the important parts of the asset lifecycle cost, the AR is expected to address the abovementioned issue, hence improving its efficiency and performance (Konstantinidis et al., 2020).

2.3.1 AR in hydropower

The potential of AR in the hydropower sector for the planning, designing, construction, operation, and maintenance of the power plant is promising, like in any other sector. The AR in planning and design can be used for better visualisation to select the design alternatives, planning project activities and health and safety of the site, visualising the risk assessment in terms of construction and operation, etc.

During the project's construction, AR can be used to supervise and monitor the project progress and design compliances, lookahead activity planning by visualising the 3D model at the site, health and safety monitoring, etc.

For the operation and maintenance of the power plant, AR has the potential for training the recruits, guidance during the operation and maintenance of the components without having to refer to the 2D drawings and paper-based instructions and collaboration with experts from a remote location. The AR also has the potential to inspect and monitor the hydropower plant components such as dams, powerhouse structures, hydromechanical components and electromechanical equipment (Trindade et al., 2019).

The BIM-based AR technology would enable the operator to efficiently manage the assets and their performance. It will enhance the operator's capability with better visualisation aspects to comprehend the task easily, minimise human errors and reduce the time to perform the task, which is critical for the machine's performance and cost reduction.

The feature of AR allowing the user to see the virtual objects in a real work environment lets the user know the 3-dimensional position better than conventional paper-based drawings or 2D displays. The AR can enhance the navigation of the components, reminding the hazard area and displaying critical information about the components that are often unavailable at the site (Ishii et al., 2007). It can display the correct position and connections required to avoid errors.

2.3.2 AR for maintenance of hydropower power plant

Implementing an AR system for maintenance would require developing the BIM model, digitalising the maintenance manuals, creating an AR model and using of AR model (Meža et al., 2014). The BIM model development would require creating the 3D model of the components, which is georeferenced/referenced so that the AR system can track the user position and accordingly display the virtual information superimposed with the real-world view from that position. The recently constructed power plants might have 3D models if it was developed on the BIM platform. As many of the power plants are old and were developed conventionally, 3D laser scanning or 3D modelling using suitable applications is required for 3D model development. Alternatively, digitised 2D drawings and photographs of the component may also be used if the 3D models are not available and expensive for development, similar to the AR prototype developed and used for maintenance of a helium flushing system by Klinker et al. (2001).

The maintenance manual and pictorial representations of tools and sample pictures (if any) can be digitalised, which will be displayed by the AR system while carrying out the maintenance activities. The AR system may be developed using the AR software development kit (SDK) or the readily available AR applications in the market. The suitability of the AR applications available in the market needs to be assessed based on the tracking and registration technologies, display technology and capability of AR display devices to support the application. As the research is for maintaining a hydropower plant where the components are mostly indoors and aiming to use portable handheld devices, the tool for the

AR system needs to be supported by mobile devices or tablets. The indoor use tracking system needs to be a hybrid system as the GPS signals are poor indoor, and all components are unsuitable for attaching the markers due to their small size.

The BIM model and the digitalised manuals/guidelines are connected and viewed in the AR system, where each step for the maintenance is linked to the relevant part of the components. The AR system can store, retrieve information on maintenance steps, and visualise and share information (Klinker et al., 2001).

While the use case study of AR in hydropower plant maintenance could not be found, the articles on maintenance of nuclear power plants, vehicle engine maintenance, etc., are available. The use of AR for maintenance from similar settings could be referred to develop the AR for maintenance of hydropower plant components.

Klinker et al. (2001) have developed a prototype for maintaining nuclear power plants. The maintenance was demonstrated for the helium flushing system. In the traditional maintenance method, technicians referred to paper-based manuals and a checklist for a particular task. The checklists were marked after meeting each requirement. Though it served the purpose of the complex system and safety aspects of the nuclear power plant, it was found cost ineffective and error-prone as the technician is limited to the manual and checklist given to him. Any issues outside the given manual and checklist must be dealt with separately, which requires the technician to return to the office to get the instruction and checklists. Therefore, the mobile augmented system was considered as an alternative system that stores all the manuals and users can retrieve them instantly.

The team digitalised the work procedures into a digital version and stored them in a database where the user retrieved, transmitted, visualised, and generated the digital instructions. The instructions were retrieved from the database based on the user's location and work context. The technician was equipped with an HMD for augmenting the real environment by displaying information such as arrows and labels of the components and an LCD screen as a secondary display for displaying longer descriptions, specifications, prerecorded videos and other relevant data.

As per Klinker et al. (2001), the prototype has three systems – one system to store the digital contents such as manual, checklist, specifications, etc., which have one or more server; a second system is the network system which controls the flow of information to the user interface with caching and prefetching features to boast the network performance. The access statistics and context information, such as user location, work order and list of historical information requests made by the user, were used to predict and preload the documents on the mobile device. This feature allows the system not to overload the mobile device with unwanted information or load insufficient/wrong data. The third system is the mobile user interface and AR system. The user interfaces with a mobile device as a secondary display are connected to the server via a wireless network for information retrieval (prefetch), temporary storage and execution of instructions. It enables the linking of geometric and non-geometric information along with sequencing of the procedures. The AR system tracks the user's location and orientation to display the information in HMD. It uses a vision-based fiducial tracking with a simple marker of the black circle and a natural feature tracking method using the component image for further correlation.

As the prototype developed was focused only on the AR system, the tracking system's performance was not assessed, but the issues with the system were highlighted. The semantic link between each step in the digital manual and relevant geometric models/components was essential. Still, the AR system could fail if the links are not processed correctly. The author proposes to use the AR system to manipulate and update or give feedback on the links through the AR system, where the semantic links between the instructions and the model component are inserted at the site.

Reusing the scene or model rendered by the mobile device is recommended for performance improvement. It can be done by not embedding the particular instruction or information to the geometric model- the instructions to be maintained in the user interface and the model to be maintained in the AR system. It enables the upgradation or modification of the geometrical model.

The information developed has to be displayed differently based on the user interface and devices. When the procedures are to be displayed in HMD, one step at a time needs to be displayed with some instruction, whereas, when it is to be displayed in other secondary devices, the whole set of procedures can be displayed. Therefore, the information layering by mode of interaction interface (device) demands the information be tagged and structured, which is time-consuming and difficult to resolve (Klinker et al., 2001).

The use of network service with prefetching of data for smooth performance is found to be effective. Still, the influence of data prefetching by prediction is low when it doesn't have sufficient prefetching statistics, especially at the initial stage of implementation. The bandwidth is consumed every time the device prefetches the information and renders the model. The multiple users carrying out the work nearby could share the rendered information to reduce bandwidth consumption.

In other studies by Ishii et al. (2007) and Shimoda et al. (2004), the researcher has focussed on various technologies of AR for the maintenance of nuclear power plants. The team studied on optimisation of the tracking method of AR and its implementation. Shimoda et al. (2004) have developed an AR system to isolate the water cooling system during periodic maintenance in the nuclear power plant. The conventional method of isolating the cooling water system for maintenance involves the field workers seeking the particular valves from the number of valves and operating them as per the paper-based instruction.

For any maintenance of the equipment, as per Shimoda et al. (2004), the first activity is isolating the system, such as the electrical power and water system, before carrying out the main maintenance task, which involves the acquisition of data before disassembling, disassembling, cleaning, condition assessment, exchanging parts, assembling, verification of its operability, connection to the system (electric and water) and functional check before putting it in operation. This process was time-consuming and prone to mistakes as the power plant had hundreds of thousands of valves with a unique ID and some congested in one place. The operators have to correctly operate the valve and should confirm the ID as there are similar valves in the same place. As the area is huge with many equipments, it was difficult to remember the valves' location. Therefore, the AR system with radio frequency identification (RFID) technology was developed to resolve the above issues. RFID was used to verify the correct valve and AR to navigate to the valve location and guide the operation process. The RFID tag, with identification data embedded in it, was attached to each valve where the scanner/reader confirmed the correct valve ID for operation instead of comparing the ID on the valve with the ID on the paper-based instruction manual.

The AR prototype developed has four functions: navigation function to show the direction to valve location when it is out of view, indication function to mark the particular valve by superimposing a virtual object over the physical valve when it is within the view of the operator, valve confirmation function to scan the RFID and verify it and the management function to guide the maintenance process.

The ARToolKit was used to develop the prototype. The system interface requirements for such tasks were minimum restrictions on workers' movement and minimum steps to use the system. Therefore, the prototype was tested using the experimental environment having similar settings with valves. The AR markers and RFID tags were attached to the valves.

The prototype was assessed for time to complete the task, the number of errors using the tool, the operator's mental workload using the NASA-TLX tool and usability of the tool. The experiment was conducted for paper-based instruction and using an AR system with wearable and handheld devices such as compacted screens connected to laptop PC, tablet PC, HMD etc. The author states that handheld and wearable devices play different roles based on the nature of the task; for example, if the task requires two hands, a wearable may be more efficient. The handheld device needs to be lighter as the user expressed discomfort lifting the device for a long period when the components are at higher levels. The factors such as the operator's experience at the area and equipment location and user's acceptance and ability to cope with new technology are influencing the assessment criteria. However, the new technology is considered to have an advantage when the operators are new and don't have the equipment's location map. The development of tracking markers was tedious and time-consuming, where many markers had to be attached to the valves, and their position had to be registered in the system.

Ishii et al. (2007) have researched optimisation of the AR marker as it is one of the critical factors for implementing the AR system. It was done by using a mix of circular and line markers and changing the position of the markers to reduce the numbers required without compromising the quality; else, huge numbers were required, taking a long time for preparation. The circular maker was designed so that it can be detected from a closer distance of about 30 centimetres up to 8 metres away using two-layer mode and was found to have better coverage by almost twice the distance of a square marker. It was a combination of a black and white circle of various thicknesses. The second type of marker was a line marker and was ideal for thin components such as smaller pipes or surface areas where the circular marker doesn't fit. It was a combination of black and white elements. It was found to be detected from a maximum distance of 11 meters. The markers were optimised by combining different marker types and using multiple-camera units and gyro-sensors. Using multiple camera units gave a wide-angle view and reduced the number of markers required. Gyrosensors were connected to the system to prevent the blocking of the view.

The authors state that the fiducial markers or feature points alone are not sufficient for reliable tracking, and therefore, it might be a solution if used simultaneously. Combining various tracking technology is expected to give a reliable tracking solution. The authoring of the AR content was found to be painstaking and more development of efficient authoring tool is required.

In the automobile industrial sector, an AR system known as mobile AR maintenance assistant (MARMA) was developed to maintain the manufacturing plant's components by Konstantinidis et al. (2020). The prototype developed can navigate to locate the component in the manufacturing plant and visualise the maintenance instructions using the handheld device. It is expected to significantly reduce the maintenance time on understanding paper-based instruction. The team used tiny-YOLO architecture (a light version of YOLO) to detect the real-time object, Autodesk Inventor Pro 2018 for developing a 3D model of the components from 2D paper-based drawings. Vuforia, a popular SDK, was used for the AR application development as it has faster performance for partly covered recognition, a robust tracking system and better performance in low light conditions. Unity was used as a 3D engine due to its compatibility with the Vuforia SDK plugin, with several predefined functions for developing interactive content.

The AR system was developed by extracting the set of features of the machine from various angles and distances, and it is stored as a 3D target model in the database. The use of an AR system entails matching those features with the captured scene to further compute the machine's position, orientation and distances before the display of maintenance instructions. The prototype was tested for the maintenance of the vehicle's A/C compressor. The target model was developed using the Vuforia object scanner feature in various lighting conditions. The 3D model was developed from the 2D paper drawing using

Autodesk inventor. The paper-based maintenance instruction, such as removal of bolts and frontal phase, unscrewing the sheet metal, replacing the gasket and cleaning the metal flange, was digitalised.

The android smartphone with 1.8 GHz 4-Core CPU and 4GM RAM was used for the demonstration. The AR system enables the user to follow maintenance instructions with short descriptions and displays of 3D objects to guide the maintenance work in sequence. It states that the prototype was assessed on the maturity level and its application in the automobile industry by more than 20 experts from manufacturing companies and received positive scores with confirmation of its applicability to the industry. The experts were interested in the technology as they felt the AR system could reduce the repair time by 30% compared to normal processes and train new maintenance operators, which would reduce the time required for training. The framework of MARMA is not limited to the manufacturing environment but can also be adopted in the investigation, infrastructure, education sector and more (Konstantinidis et al., 2020).

Trindade et al. (2019) developed an AR prototype for inspecting and monitoring dams as a new approach to safety control measures. The AR was used to display all the safety monitoring sensor readings and their locations in real time, enabling the operators to visualise the in-situ structural health information of the objects. The traditional method of monitoring structural health using sensors is done by acquiring the readings from the data logger, analysing them using relevant tools and inferring the structural condition at the individual sensor location. Therefore, the prototype was developed to give the dam inspection team an overview of each sensor's location and visualise the structure's health.

The prototype was developed to be used from a single point of observation downstream of the dam, which gives the overall view of the structure. It comprises four components: data API, interaction module, AR SDK and visualising module. The data API is used to load and parse information from the database. The interaction module connects the database with the other two modules, AR SDK and visualising module. The AR SDK is used for tracking and object recognition in the system. The visualising module is to render the virtual information based on the AR scene and displays the final information for visualisation. The prototype was developed using a Unity graphical engine with Vuforia as AR SDK.

The user interface allows the safety monitoring inspector to navigate through the different visualisation menu and toolbars, which displays the live data of each sensor along with location and relevant information. The image target tracking method for the marker in the AR system was used for tracking and calibration as the particular dam for which the prototype was developed doesn't have distinct features at the downstream side, such as a spillway, gate etc., to use the markerless tracking technology. The alternative features on the powerhouse were used for tracking. The location of sensors in the dam body is determined and overlaid to the AR scene by matching the features captured by the camera and the features in the target marker. The authors found that the use of image targets was less affected by variation in lighting conditions, although its performance was low. The performance was improved by using the multiple images taken during different day periods as image targets.

The prototype was tested and found that the system could detect the targets at a distance of about 110 m to 200 m; however, variations in light luminosity influenced the detection. Vuforia's extended tracking feature was used to extend the field of view to cover the area that doesn't have a tracking marker. The user experience was assessed: the tracking was reasonably stable and users were satisfied with the prototype (Trindade et al., 2019). Such techniques could be used in other areas for monitoring and inspection, such as equipment inside powerhouses and underground caverns, which are traditionally being monitored.

2.4 Potential of AR and BIM in the hydropower sector

The revolution of digitalisation technologies in the AECO industry has paved the future of the hydropower sector to become more efficient and cost-effective by using the right methods. The technologies of AR and BIM are evolving and yet to become ubiquitous tools in the industry to adopt by everyone. The initial investment cost is higher for the small players in the industry and would need a significant cost reduction to become a ubiquitous tool. However, the future of digital technologies is very promising for developing and managing assets.

The design and planning of structures on the BIM platform, including the geological information and using it in the AR system to visualise the site, would enable the designer to know the limits of the proposed designs, such as the extent of excavation and stability issues with it, constructibility issues and more. It would give a better realistic understanding of the site condition. Since the components of the hydropower span over a large area, using a drone over the area as an input sensor (instead of a camera) would enhance the visualisation of the large area. The manipulation of 3D modelling and basic modelling using AR at the lab and design studio was researched by Hagbi et al., (2010); Bergig et al., (2009); Henrysson et al., (2005); Ledermann and Schmalstieg, (2005; Piekarski and Thomas, (2003); Baillot et al., (2001). With the advancement of technologies, the relevant BIM model could be developed or modified using an AR system based on the site's actual condition in real-time. The analysis and design may also be carried out instantly, and review the model to suit the site condition. The future of BIM modelling could be through AR in a real-time environment where the user can propose the solutions of the projects at the site rather than in the office. The modelling of the components at the site would give the proposal a better understanding and clarity.

Developing a digital twin of the hydropower plant with a BIM model would enhance the visualisation capacity of the operators. The live operational data such as power generation/demand, river inflow/outflow, reservoir level, weather status, vibration, temperatures, turbine revolution, pressure in the penstock, noise abnormality and other mechanical and electromechanical data along with structural monitoring data such as cavern stress/strain, seepage and foundation pressure of dam and powerhouse, block joint meter, etc. can be connected to the BIM model, and the analysis tools determine the condition of the components and structures in real-time. The live graphical display of these data and analysis results, along with the trend and prediction using the AR system, would enable the operator to understand the situation of the power plant faster and better. The operator doesn't have to go to the control room to check those data or carry out the analysis after the data collection. The BIM manages the components' data, the digital twin makes the BIM model dynamic with real-time data, and AR enhances the visualisation ability of the user.

The inventory management of spare parts, tools and accessories required for the equipment maintenance can also be linked to the model where the AR system could display the relevant information such as material stocks, specifications, suppliers, etc. while inspecting the structures and equipment. The inspection and monitoring of the assets using the AR system connected to the digital twin would give the live status of the components using the data from the sensors (IoTs). They can also view the equipment condition if the condition monitoring data are linked to it.

Therefore, the BIM model connected with monitoring sensors in real-time is the main component of the digital twin and augmented reality. It should have not only the 3D geometric information but also other relevant data for the lifecycle management of the assets. The BIM will enable the management of the data required for digital twin, augmented reality and other future technological evolutions.

2.5 Challenges to implementation of AR and BIM

The available tools and solutions for AR, BIM and other digital solutions are fast evolving over the period, and new challenges are faced, such as the suitability of the tools and their interoperability, limitation with current technologies, upgradation of the tools with changes in technologies, availability of the skilled manpower, etc. The reluctance of organisations and users in the AECO industry to embrace the change also contributes to the slow embracing of the digitalisation process. As the industry involves various stakeholders and a highly fragmented group with differing roles, the risk taker for disruptive change is the least due to a lack of clear benefits and incentives (Criado-Perez et al., 2022). According to Criado-Perez et al. (2022), the lack of leadership to spearhead the strategically driven investment, transformation and collaboration is impeding the adoption of the technologies in the industry. The transformation is mostly based on the reactive mode and the reason for the industry lagging compared to other sectors. The shortage of key skills and knowledge also contributes to the slow adoption of the technologies.

As the industry involves various fields of expertise and uses numerous tools and devices for the solutions, the sharing of data and information are often faced with interoperability and integration issues, and it is one of the factors impeding effective collaboration and communication (Ahmed, 2018; Shehzad et al., 2021). When an organisation changes the tools to better suit the requirements, the data from the previous system are often not usable or lose critical information while integrating it.

Therefore, buildingSMART, a global community focussing on open digital ways of working, is developing and promoting the standards with a concept of openBIM to work more efficiently and collaboratively for the entire project lifecycle. The openBIM concept is promoted in the AECO industry from asset owners to entire supply chain stakeholders where the digital workflows are vendor-neutral formats such as industry foundation class (IFC), BIM collaborative format (BCF), construction operative building information exchange (COBie), etc. (buildingSMART, n.d.). The loss of information still exists while sharing the data from one tool to another. Therefore, the information exchange is expected to be free from such issues, with more vendors committing toward openBIM and new developments.

As the size of the model and information for the asset is expected to increase over the year due to the increase in the scope of BIM uses along with increasing dependence on wireless connections for data exchange, a more efficient way of retrieving, sharing, uploading, collaborating etc. is required. The quality of the AR experience depends on bandwidth to access database servers, information exchange, data processing, visualisation, etc. The real-time accessing, rendering, visualization and processing of the model, collaboration with experts remotely and interaction of IoTs with the model would require high internet bandwidth and speed communication channels with low latency. Therefore, implementing a 5G internet communication system will enhance the AR experience with better performance.

3 METHODOLOGY

As the hydropower plant is one of the complex areas in the industry, the research aims to explore the potential of augmented reality and its challenges in managing and maintaining hydropower plants in the context of building information modelling. The use of AR in the management and maintenance of hydropower plants is expected to improve the performance of field operators. The information on BIM and AR from use case studies in various projects and industrial sectors were referred to study its potential use in the hydropower plant.

The thesis contains the general background on hydropower, a review on building information modelling, augmented reality and its working principle, digital solutions in development and a review of case studies in the context of the hydropower sector. The working principle of AR has been explored with the technologies in development as it is the core of the AR system for better user experience and performance. Most of the AR literature referred to is from other sectors such as maintenance of automobile manufacturing plants, nuclear power plants and building projects due to limited resources in the hydropower sector. The concept and methods from these sectors are applicable for implementing an AR system in hydropower plant management and maintenance.

As all hydropower plant in operation doesn't have a BIM model, the previous case studies of the development of AR system in other sectors for both project having a BIM model and without a BIM model has been reviewed. The method to develop an AR system has been discussed in relevant sections.

Therefore, the potential use of AR has been presented for the maintenance and inspection of hydropower plants. The components of the AR system, the tools and workflow for developing the AR system and the flowchart on how the AR system functions for the maintenance or inspection of the power plant are presented. The future development of AR, along with its challenges and benefits in the hydropower sector, has also been reflected.

The AR demonstration at the power plant was not done as the development and implementation of the AR are similar to any other projects or assets with a slight difference in the environment where the task has to be performed, location of components and technologies used by the software. Moreover, the demonstration would not be possible when the power plants are live and need to schedule with the power plant's shutdown or maintenance period and would require a longer duration for it.

The full-scale prototype would require optimisation of marker position/types at the field and information updates to the database while testing its performance.

4 DEVELOPMENT AND IMPLEMENTATION OF AR SYSTEM

The following sections describe the existing power plant maintenance and inspection methods along with the development process of the AR prototype. It also describes how the AR prototype should function with the required features and resources.

4.1 Existing methodology of management and maintenance

The automation and digitalisation of the operation and maintenance of hydropower plants worldwide are at various maturity levels. The hydropower plants developed or modernised recently are equipped with better technologies and smarter solutions for the operation of the power plants. The stakeholders for the power plant are increasingly gearing towards the smarter decision-making process by modernisation and upgradation of old power plants. The conventional operation and maintenance of hydropower plants still exist in many parts of the world. The complete switch to the digital solution still requires the technologies to be a ubiquitous product and low capital cost for implementation. The older hydropower plants are in a phase of modernisation and upgradation with the SCADA system for power plant operation. The use of digital technologies in O&M is increasing with the evolution of IoT.

However, the power plants still depend on manual inputs for the maintenance and inspection of the components. The trained manpower uses paper-based instructions and manuals to carry out the task. The experience of the manpower matters a lot for the performance and reliability of the task carried out. For quality assurance, the field operators are made available with the instructions, drawings, specifications, checklist and other relevant information while performing the task. If the operators are less experienced, he/she has to clarify doubt from supervisor or colleagues nearby, which would take more time to comprehend the work. The recruits are trained under the guidance of experienced operators.

The operators for maintenance and inspections are generally grouped based on different trades/specialised areas of their skills, such as mechanical, civil and electrical trades. The operators specialise in the skills required under each category for better performance. The resources may be centralised for sharing among the power plant under the organisation or has a dedicated team for each plant. The maintenance or inspection activities are carried out as per the instruction or manual, and the checklists are used to ensure the quality of the work performed.

The maintenance and inspection activities are scheduled and carried out at different intervals. They may be done weekly, monthly, quarterly, annually or after a certain period of operation as per the recommendation from the designer or equipment manufacturer. As the machine downtime reduces revenue generation, each group is expected to complete the task within the scheduled period with the required standards. Any extension of machine shutdown or unplanned shutdown while operating the machine after maintenance would significantly cost the organisation. As reported in the literature, the risk of human errors or spending more time to eliminate the errors also increases when under pressure. The errors may be in measurement issues, assembly of components after maintenance or substandard work. To eliminate the errors, each organisation has their method to manage such risk, and the operator tends to spend more time making the work error-free.

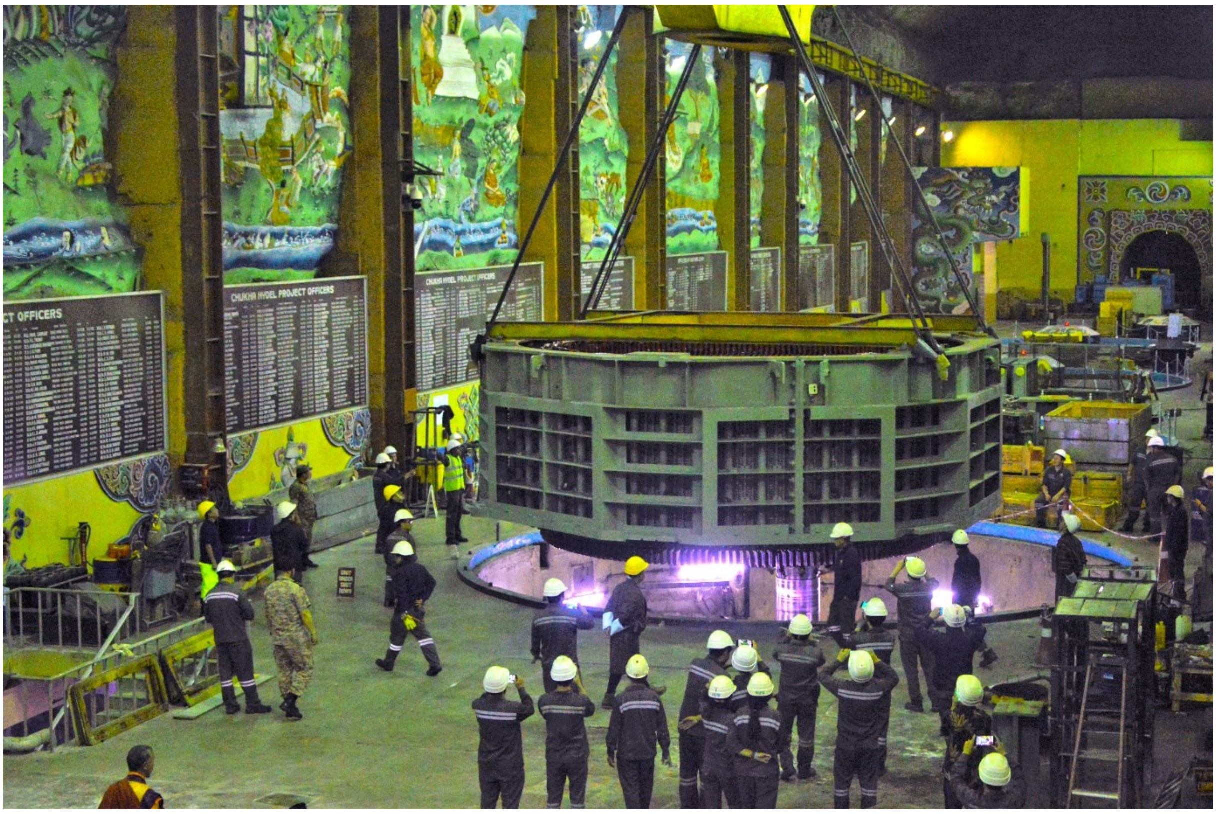

Figure 10: Lowering of stator after maintenance (Courtesy: Media Officer- DGPC)

Some of the major components in hydropower plants (EPRI, 2005, 2001a, 2001b, 2000) requiring timely inspection and maintenance are:

- DAM/Intake structures: gates, seals, spillways, trash racks, cleaning machine, sensors, desilting chamber and fish passage
- Turbine and auxiliaries: MIV system, by-pass valve, nozzle assembly, deflector system and runner
- Synchronous generator: rotor, stator, collector ring, brush gear and bearing assembly
- Hydraulic governor actuator, cooling water system, crane and transformer
- Switchgear equipment: circuit breaker, vacuum circuit breaker, isolators and compressors

4.2 AR development process and workflows

The use of the digital solution is expected to enhance the cognitive level of operators to better the performance and reliability of the task carried out. The AR will not replace the required manual input but will enhance the comprehension of issues or tasks performed at the site.

The following section describes the possible solutions for developing and implementing AR in the hydropower sector with two scenarios of power plants with a BIM model and without a BIM model.

4.2.1 AR components

The important aspect of implementing AR is the availability of information in digital versions, such as geometric data, specifications, manuals, photographs etc. The use of AR technologies and complexity will vary based on the information available and the level of investment for the development. The information access and management, along with the integration of information to the AR system, need to have a different method of technology in the AR system for power plants with a BIM model than those without a BIM model.

The implementation of AR for the power plant with a BIM model is similar to AR applications in other sectors such as building, manufacturing, industrial plants, etc. However, the right AR system has to be adopted for better performance. As the location of power plant component varies with some on the surface and some underground, some at a more open location and some in a deep narrow valley, the technologies in the AR system has to suit the environment for an accurate determination of position and orientation, the capability of AR device to carry out real-time rendering and visualisation of the objects/scene and manipulation of the information. The standalone tools available in the market may not suit the requirement for the given operating environment and may need to customise or select another for the requirement. The development of the AR system using the SDK would require skills and resources but can be customised to the requirement of the required environment.

The implementation of the AR requires a database and the AR system, which includes software, hardware and user interface. The details of each component are given below:

Database	**AR System**		
2D/3D model	**Software**	**Hardware**	**User Interface**
O&M manuals & specificatic	Tracking and registration	Processor	Input command
Photographs/video clips	Retrieve information	Sensors	Navigation
User Data	Processing feedback	Input device	Display processed information
Data logger	Model visualisation	Display device	Information exchange

Figure 11: AR component

Database: The AR displays the virtual geometric and non-geometric information, which forms the basis for augmenting the reality to the user, which will enhance the understanding of the environment. When the power plant or any other project has an as-built BIM model, all the geometric and most non-geometric information are expected to be available in the model. Only some information may have to be incorporated based on the information richness of the model. Therefore, the powerplant with an as-built 3D model, material classification and specifications and its operation and maintenance guidelines would be the starting point for implementing AR. The AR technologies used in such cases require less site preparation and information processing, unlike projects without a BIM model.

For the power plants that don't have a BIM model, implementing AR would require considerable time and resources to prepare the information. The extent of preparation would depend on whether the BIM model is to be used for multiple purposes or just for one specific task. The operation and asset management would require the detailed modelling of the power plant by incorporating all the geometric information, specifications, maintenance timeline, recording of operational records and maintenance, etc. The 3D modelling can be prepared using tools such as 3D scanning and preparing model by referring to the 2D drawings. The AR for maintenance could be done in isolation using the available 2D drawings, equipment photographs and clips. However, the preparation of the site beforehand and AR content authoring would be longer than BIM-based projects. The AR system technologies will also have to be varied, especially for tracking and calibration technologies.

The detailed maintenance guidelines issued by the equipment supplier or designer for maintenance and inspection of the particular equipment, the as-built drawings/model and specifications are converted into digital versions for the AR demonstration. The use of an AR system for all the components may not be possible due to accessibility and safety issues. Some components are taken out to the open area for further disassembly and maintenance, and the use of AR would be more convenient in such cases.

Other information, such as user details and their privileges and data logging to keep a record of the task carried out by the user, is also required for audit trails and security controls. The users would be the field operators and the admin to manage the information model. The admin has full privilege to add/modify the information, and the field user can upload feedback/comments and access the information. The digital version of the paper-based O&M manuals and instructions, photographs of the equipment and its parts and video clips (if relevant) are some of the information that will be stored in the database for use in the AR system.

The database may be stored locally in an AR device or the cloud, which can be retrieved using wireless internet facilities. However, the bandwidth of the internet service may influence the performance impacting the user experience. The signal coverage to all the component areas will be required for optimum performance of the AR system.

AR Software/Hardware: The software in the AR system needs to process the input command for augmenting the real world with virtual information. The method of tracking and registration/calibration in AR is the critical factor in influencing the user experience as there are several methods of tracking and registration of the scene captured by the camera, each one suit different scenarios. The combination of all tracking methodologies may impact the processing performance of the device. The site preparation of tracking features/markers, model preparation, and non-geometric information processing would vary with the method used, which ultimately depends on the type of data available.

If the power plant has a BIM model, the model-based tracking under a vision based- visible light tracking group and a mix of inertial trackings are recommended. The preparation at the site is also minimum as all the model information in the 3D model is used to determine position and orientation, and it doesn't require markers to be placed at the site beforehand. The model-based tracking, also known as markerless tracking, uses the algorithm to map the area and compare the features detected in the image with the virtual model in the database to determine the position and orientation of the camera. It uses the natural features of the objects around it instead of artificial markers prepared by the user to determine the position and orientation of the user. The tracking algorithm, such as SLAM and other modified or optimised versions of SLAM, such as PTAM, LSD SLAM, and vSLAM, ORB-SLAM are used for tracking and calibration in model-based tracking method. However, the performance of the model-based tracking method is influenced by factors such as similarity in the shape and texture of the objects, lower contrast of object and its background, and inability to detect the unique features of objects due to low intensity or high-intensity lighting conditions, interference by the reflection of the light and the lighting of the area with a general incandescent bulb instead of focus light which has better performance (Hantono and Yudiantika, 2015).

For the older projects and power plants which doesn't have a BIM model, it could be developed by using various technologies available in the market depending on the complexity of the projects, such as 3D laser scanning and modelling or alike to prepare a 3D model in case of complex projects or manual modelling of the components using modelling tools for a simpler project as it is cheaper than scanning. Alternative, the AR may be implemented using the available 2D drawings and images with animated textual instructions and symbols on the screen to augment the inspection or maintenance process. The AR will display the instructions along with the symbols or directions to the operators when it scans the marker, which needs to be prepared beforehand by the user. However, preparing the markers for tracking, taking pictures of the individual components/parts and fixing to the point with a known coordinate or position would be tedious. As the component size varies from small diameter pipes to components with large surface areas, the single type of markers will not be sufficient. A mix of fiducial markers such as circular code, square and line/bar code will be required, and the coordinate of each marker for the object is noted for navigation purposes. The natural features, trademarks or photographs of the object with unique features would also contribute to the tracking.

Tracking photographs of the component with trademarks or unique features can also be used when the component position is not fixed; for example, a pump may be moved to the repair bench for repair or maintenance. Tracking using the photographs of components in other areas, such as moving components, components with varying temperature environments, etc., would be required as fixing the fiducial markers on it is impossible and would cause safety risk due to melting or burning of the markers.

Irrespective of the project having a BIM model, the AR system prototype (software) may be developed using the various AR SDK or the standalone AR tool available in the market. Since the available AR tools in the market are not specifically available, the new tool may be developed to suit the specific requirement. An adequate trial is required for customised or readily available tools to check performance and efficiency. The most widely used AR SDK is Unity 3D engine with Vuforia SDK for the AR system. The tools have several predefined functions and libraries for developing interactive AR content. The Vuforia supports all kinds of tracking methods such as fiduciary marker, markerless tracking, image targets and more. The platform enables the user to develop the application for all types of device operating systems.

For the hardware, mobile device such as smartphones and tablets of current generations has sufficient processing capacity, which can support the functions of both hardware and software. Since smartphone ownerships are high, it would be easier to implement the AR system using smartphones. The hardware such as compass, accelerometer, camera, gyroscope, display screen, and processors of sufficient capacity makes the use of smartphones feasible for AR implementation. A computer laptop or desktop is required to prepare the information and author the AR contents.

User Interface: The user interface enables the exchange of information between the user and the system and visualises the information. The smartphone has features for input command, navigation, information display, exchange of information, etc.; therefore, it doesn't need separate setups for the additional interfaces. These interfaces are accessed using the information browser arrangement via its touchscreen and speech recognition functions. After determining the position and orientation of the camera, the system displays the superimposed virtual models over the real-world scene along with the name of the components, their maintenance or operation instructions, and other relevant information required to complete the task. The user logs into the system to access the data based on their privileges, browse/navigate through the instructions by tapping on the back/forward button, feed in the observation or comments by typing the information or taking photographs, and mark the checklist after completing the activities, etc. The information browser will record the activities carried out, user details and timestamp of activities and any other information shared by the user. The system will alert the admin when the field user uploads the information or comments, which will be resolved or escalated to the relevant person based on the comments or observations.

4.2.2 Workflow for AR system development

The following activities, grouped into three categories, need to be carried out to develop the AR system using the AR SDK, and the workflow for the development is presented in Figure 12.

Collection of data and planning: The data of the power plant components need to be collected for AR content. These data are a BIM model or 2D drawings, photographs of the components, manuals converted into a digital version, user lists, and media clips for additional information. The 3D coordinates and dimensions of the components, along with the coordinates of marker origin, are also collected. As the powerplant complex is huge and the components are mostly indoor, at multiple levels in the case of an underground powerhouse, the data are classified into the type of activities (maintenance or inspection) and name of components.

The additional information may need to be collected/updated while preparing the database in AR SDK, and also the fixing of the markers is done after generating the markers.

AR content preparation: The main task for the development of AR is under this category where the tracking, visualisation and linking of interactive instruction are developed using Unity 3D engine with Vuforia SDK. The database of the object tracking marker is created using the appropriate Vuforia target generation tool, such as a model target generator for BIM model-based markerless tracking, an image target generator for image marker tracking and VuMark for fiducial marker tracking, etc.

The component photographs, unique signage at the field, fiducial markers, 3D models etc. are used to generate the tracking markers. The database is imported to the Unity 3D engine, where relevant configuration and scriptings are carried out, assigning the marker database to the object or interactive instructions to be displayed when the device captures the target/scene. The AR system developed is simulated to check its performance and errors before exporting/saving as an application for the device based on its operating system.

As the fiducial markers at the site are not feasible in all locations or components, some markers are generated using images of the components or the unique natural features around them. These image-based markers should have the following characteristics for better stability of AR content:

- The image contains unique features or patterns
- Each feature/pattern is in contrast to an adjacent feature
- The pattern or image is asymmetrical
- Not too glossy print to avoid the light reflection

When the components have too many parts to be disassembled or assembled, the use of image-based markers will reduce the fixing of fiducial markers on each major part, which may get damaged over the period, and the unique features on the image may not meet the marker qualities required. Therefore, the hybrid tracking system with an alternative arrangement, such as scanning smaller components for model-based tracking, using fiducial markers such as QR codes and line/bar codes for individual parts, image markers and other similar methodologies.

Implementation of the AR system: The prototype is installed in the device to test at the laboratory/site for further optimisation. The optimisation would require using additional markers or changing the position for better performance and avoiding occlusions. The lighting condition of the area will also influence the marker or model detection performance, for which the lighting condition of the area may need to be modified. Suppose the database is to be retrieved from cloud storage. In that case, adequate wireless communication facilities will also have to be provided, covering all the areas where the AR system is to be used.

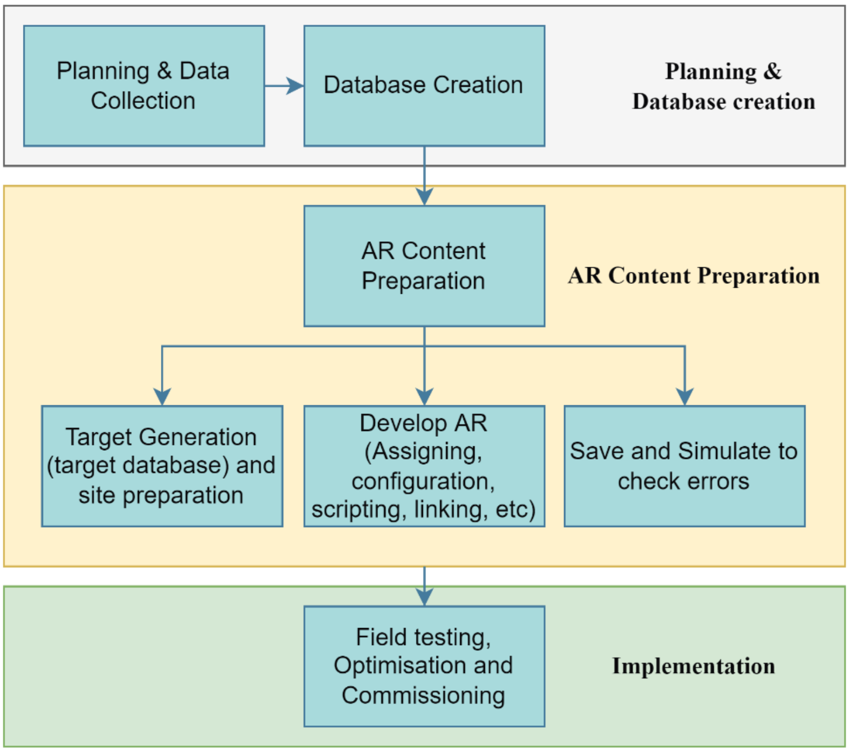

Figure 12: Workflow to develop AR system

4.2.3 Operation of an AR system in the field

The AR application for handheld-based devices is the preferred one owing to the high ownership of the smartphone and the capability of the operating system to handle the processing complexity of the AR system developed. The database is stored on the device itself for smaller tasks. However, cloud-based storage is required for better performance for the larger database with 3D models and media contents. An adequate wireless infrastructure will also be required to access data from the cloud storage. The bandwidth of the internet facilities would influence the AR experience, especially when live collaborations are being held remotely with experts away from the field. The introduction of 5G internet service would enhance the user experience with lower latency and speed than 4G services.

The flowchart on how to use the AR system is given in Figure 13 and the major activities to be performed in each step are described below:

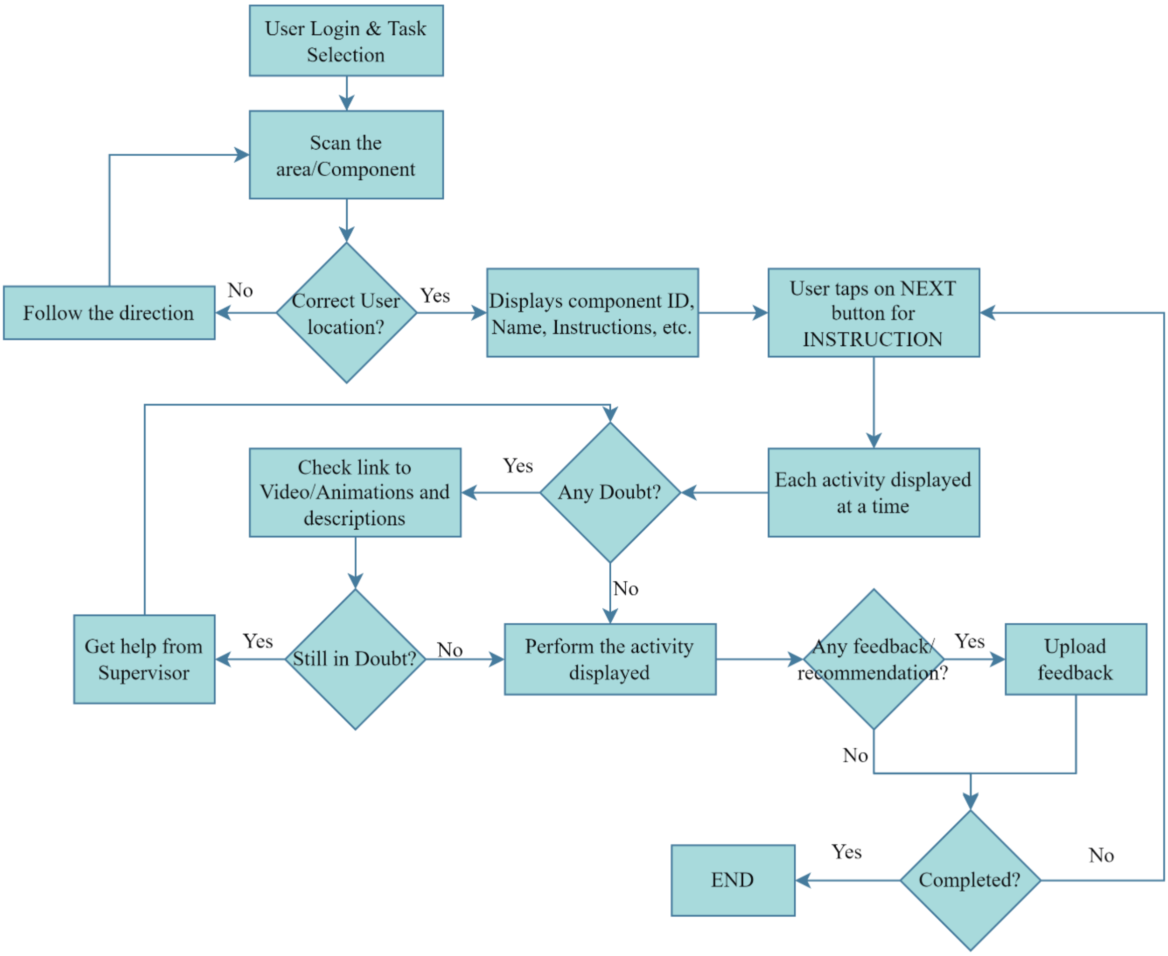

Figure 13: Flowchart for the operation of the AR system

- A user enters the credentials (field user can view, make changes to checkbox and upload the feedback for each step, whereas the app admin can change/modify the contents.)
- The user selects the task to be carried out and then goes to the component's location. If the user is unsure, the nearest marker is scanned for navigation. The user rescans the marker after reaching the site to confirm the component.
- After analysing and tracking the scene captured by the camera, the system will display the relevant information such as the virtual model, component name, ID, animated instructions and specifications.
- The display screen has a forward and backward button to browse through the instruction, and tapping the forward button will lead to the subsequent steps. Each step has a help button containing media and textual information for assistance. The user can also contact the supervisor for assistance if the available information is insufficient for understanding.
- The user performs the task based on the instruction displayed on the screen before moving forward to the next steps, and he/she can upload the feedback, photographs, video clips, etc., at the end of each task. The feedback can be on the condition remarks, information related to the future task, a record of task performed or any information which will be used by the supervisors

and concerned officials to address/plan it. The system triggers the alert message to the admin for necessary response and action. The system keeps records of each step and feedback uploaded for performance analysis and audit trials. For the maintenance of the components, the instruction starts from disassembling components to assembling them, and for the inspection, each step on parameters to be checked will be displayed on the screen.

The user login and the selection of the task are as given in the entity-relationship model from the database, as given in Figure 14.

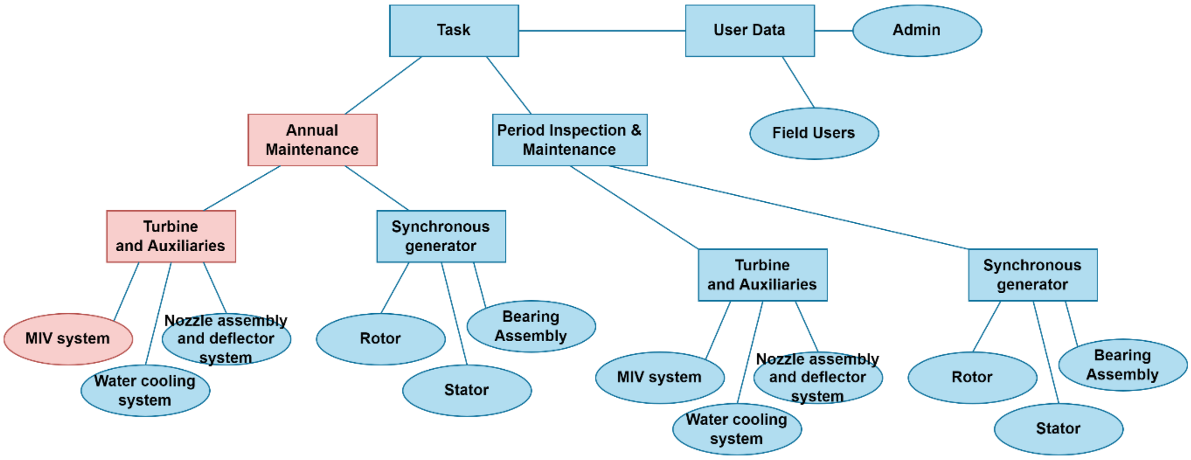

Figure 14: ER model for database

For the annual maintenance of the Main Inlet Valve (MIV) system, the user has to log into the AR application and select the type of nature of work as Annual Maintenance and the main component “Turbine and Auxiliaries” to reach the component level selection. The user then scans the marker or the scene using the camera at the back of the device to confirm the components to be inspected/maintained. The system also gives direction if the user is in the wrong location. The animated instructions with arrows and highlights are displayed along with help buttons for assistance which contain the explanation of the task. The display screen has forward and backward buttons to navigate through the maintenance steps and also display other relevant information.

The activities to be performed by the operators will be displayed in sequence as an animated text over the component along with other animated features, such as symbol-based instruction to show the movement/turning direction and location, for better visualisation and understanding along with some reference pictures, videos and descriptions for assistance. The task may be the disassembly and assembly of components along with the replacement of parts, a procedure to isolate the system for maintenance and a list of parameters to be checked and enter a reading/comments during the inspection and so on.

The AR displays each step to complete the given task; for example, the disassembling and assembling task may involve isolating the system, detaching it from the main system by removing nuts, parts removal, maintenance servicing as required or replacement of parts and assembling the parts back to its original stage.

4.3 Discussion on AR implementation

The review of various case studies suggests that AR can be implemented in hydropower for maintenance and inspection. However, like any other sector, there should be adequate preparation of the site. The AR can give cognitive assistance to operators by displaying the right information at the right time to improve their performance and reliability. The operators can perform the task faster with correct information available in a structured way using AR in the process. The BIM and AR technologies are mostly used in the design, engineering and construction phases of the project in the AECO industry. The support from stakeholders and lack of skills to use it in the operation and maintenance phase limits the organisation from reaping the benefits of digital technologies.

Several factors may influence the full-scale use of AR technologies in the real-life O&M of the power plants or any AECO projects. The financial benefits of implementing such technologies have not been assessed and it would be difficult to monetise the benefits due to the complexity of the O&M process.

The opportunities for the organisation to implement AR are:

- The training of the recruits can be done using AR and VR technologies to better understand the activities with an immersive experience instead of the theoretical instructions and photographs in the classroom. Such methods would reduce the safety risk at the site while in training and give a better understanding of the instructions and nature of work through visualisation.
- As the industries are facing a shortage of skilled manpower, using digital technologies could optimise the manpower requirement by automating and using such digital technologies wherever possible to assist the operators in performing the task.
- The AR can assist the operators in making a quicker decision with better visualisation power and structured information rather than going through the manuals and discussing/referring it to colleagues and seniors to understand it. The users are facilitated with instructions and information to perform the task and also provided the checklists to assure the quality of the work. The performance in terms of productivity and quality of work is expected to improve with cognitive assistance using AR.
- The collaboration with the experts in remote and junior operators at the site could be done to guide instead of waiting for them to reach the field for assistance. It would save cost and time as some issues can be solved without being physically present at the site.
- The AR system facilitates the visualisation of the live performance of the powerplant by connecting to the digital twin model. The information such as the status of the components, any faults or errors in the components or sensors, upcoming maintenance and inspection schedules

and other relevant data could be instantly known with the AR system. This would enhance the operator to keep updated on the status, actions required and planning of their activities more efficiently.

- The safety of the operators could also be enhanced by reminding the operators about the hazard area. The system can alert when the operator is close to moving parts of live components, edges of the working area, etc.
- The evolution of handheld devices such as smartphones and tablets has increased the ownership which could be used for AR instead of purchasing a dedicated device. More operators can participate in the operation and maintenance using the system.
- The AR can facilitate better audit trails by recording the information of the activities performed, such as the operator's details, date, time and comments etc., for performance tracking and improvement.

Some of the challenges in implementing the AR system in the operation and maintenance of power plants are:

- The willingness of the stakeholders to change and switch to digital technologies would influence the successful implementation of the AR system.
- The introduction of a new system would require training and awareness to gain user acceptance to change the way operators perform the task as users may not be comfortable using the devices and at the same time also be involved in physical activities to perform the task.
- The real positive impact could be felt once the users adapt to the new system. The new system would be a hindrance to the performance if not used correctly.
- The level of preparation of information to create the AR content would be more if the relevant information is unavailable. The development of AR content, such as tracking markers, preparing optimum lighting conditions of the area, taking good quality photographs for markers, fixing markers in a strategic location to reduce the marker numbers, etc., would require considerable time. If the plant has a 3D model, the preparation time would be less than without 3D models.
- The availability of the resources and infrastructures would also impact the user experience. With the increase in file size, the data storage will have to be in the cloud, and the internet speed and bandwidth to access the storage would influence the user experience.
- The cost of development and implementation of AR would influence the extent of involvement from the stakeholders to improve the system.
- AR will not be usable for some tasks in the field but can be used for training. It may be inconvenient to switch between physical activities and mobile devices for AR, especially when working in a confined/small area or when both hands are engaged with manual work. Even the use of head-mounted devices is also inconvenient in some cases.

5 CONCLUSION

5.1 Summary

Hydropower is one of the important sources of renewable energy and plays a critical role in grid stabilisation when the supply from other energy sources is down. Therefore, hydropower is crucial until other forms of energy can replace its role.

The operation phase of any powerplant is the longest period, spanning up to 100 years, and accounts for about 80% of the lifecycle cost. The power plants are ageing and faced with price competition from other renewable energy sources as their generation cost was going down over the years due to technological advancement. Therefore, the powerplant owners are focussing on changing operation and maintenance strategies to increase the margin and stay competitive by maintaining the lean O&M cost and maximising asset productivity.

The maintenance and inspection are an essential part of the O&M activities of the power plant to upkeep the performance and enhance the machine life. Any machine downtime, be it scheduled or emergency, is a revenue loss to the company. The O&M team strives to minimise downtime by timely maintenance and inspection of the equipment. The skilled manpower is ageing and facing shortage. The manpower is stretched across different functions to address it, and companies are challenged to optimally utilise the available resources. Automating the O&M process and maximising the usage of digital technologies in the decision-making and asset management process are some solutions to address such challenges.

Augmented reality is one of the promising technologies that can be used to assist operators in the maintenance and inspection of the power plant. Therefore, the existing method of maintenance and inspection by the operator using paper-based instruction, drawings, specifications, and parameter checklists can be replaced with AR. It can be implemented using similar concepts and ideas developed for the maintenance of equipment and engines in the military industry, the automobile engineering industry and the nuclear power plant. It can assist the operators by displaying the instruction and relevant information in a structured way, along with animated graphics for navigation and highlighting the components for action. It can also be used for training and remote collaboration with experts for guidance.

Such assistance by AR to the operator would enhance their performance without requiring them to spend time figuring out what to do. The additional information, such as the demonstration in the form of media clips, text and photographs, would reduce the time to comprehend the task with minimum interventions by the supervisor. The AR could be developed using AR SDK or use the AR software available in the market. The development of AR would meet the specific requirement but require expertise to develop it.

The preparation level to implement AR in a power plant which doesn't have 3D BIM models will be much higher. The collection of 2D drawings, site photographs, the coordinate of the markers to be fixed, preparation and fixing of markers, and determining the location of the markers are some of the additional preparation besides authoring the information for AR.

5.2 Future work

The demonstration of the AR could be carried out in the field but needs close coordination with the power plant officials to schedule the activities so that it coincides with the maintenance plan. The implementation of AR in hydropower plants would require optimisation of the process and information. Not all components are suitable to fix the markers due to their size and positions, and some components' images would not be as suitable as markers.

The study focused on AR with maintenance and inspection. However, it could be replicated by connecting to operational data, sensor data used for safety monitoring of power plants, asset management data and other relevant data. Incorporating artificial intelligence would facilitate the operators to keep track of information in real time.

6 ACRONYMS

AECO	Architecture, Engineering, Construction and Operation
AR	Augmented Reality
BIM	Building Information Modelling
DT	Digital Twin
GPS	Global Positioning System
HMD	Head-Mounted Display
IFC	Industry Foundation Classes
IoT	Internet of Things
LSD SLAM	large-scale direct monocular SLAM
MARMA	Mobile AR Maintenance Assistant
MR	Mixed Reality
O&M	Operation and Maintenance
ORB-SLAM	Oriented-FAST and Rotated-BRIEF SLAM
PTAM	Parallel Tracking and Mapping
RFID	Radio Frequency Identification
SCADA	Supervisory Control and Data Acquisition
SDK	Software Development Kit
SLAM	Simultaneous Localisation and Map Building
VR	Virtual Reality
vSLAM	Visual SLAM
XR	Extended Reality

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