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Chapter 16
Superpowers in the Metaverse: Augmented Reality Enabled X-Ray Vision in Immersive Environments

Thomas J. Clarke, Ian Gwilt, Joanne Zucco, Wolfgang Mayer, and Ross T. Smith

Abstract This chapter explores the use of augmented reality (AR) enabled X-ray vision (XRV) in immersive environments. AR XRV is the ability to render a virtual object as if it is behind or encapsulated in a real-world object. For example, a user may look at a wall in the real-world to see who or what is inside or behind the wall with the use of augmented reality. Seamlessly merging virtual objects with the real-world is challenging as virtual objects in augmented reality are typically rendered in front of the real world causing a depth mismatch. The mismatch in depth does not accurately portray the virtual object in the real-world and may lead to perception problems when augmenting the real-world with virtual information. This review provides an overview of the existing techniques, applications, and devices that provide XRV in immersive environments and summarises the current research challenges. The emergent nature of XRV in immersive environments is highlighted emphasizing the need to comprehend the challenges and opportunities of AR-enabled XRV. The overview presented in this chapter will assist researchers rapidly identify challenges as the technology necessary for XRV within the metaverse emerges as a refined capability and accepted convention.

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15.1 Introduction: Augmented Reality, X-ray Vision and the Metaverse

Many promises made by the Metaverse are based-on the opportunity of employing Virtual Reality (VR) technology that can replicate our experience of physical spaces and places. The experience provided by the metaverse can be very different when using a virtual headset compared to an augmented reality headset. The trend towards merging real and virtual worlds (XR) using these headsets raises questions about how to faithfully represent the physical world and create a way of seeing a combined reality of digital objects and real-world physical objects.

Augmented Reality (AR) is a spatial tool that can provide a window into a metaverse. Virtual items should be located through the metaverse's understanding of the real-world(Park and Kim 2022). In general, augmented reality only concerns itself with the environment that the users can see from their own perspective, but this does not have to be true for an augmented reality X-ray vision (XRV) system within the Metaverse (Milgram and Kishimo 1994). An AR metaverse could utilise an Internet of Things (IoT) network to increase the scope of the world that people can see and interact with. Within an AR-enabled metaverse, the digital information presented to users can improve their understanding of the physical world (Park et al. 2021).

For example, an AR metaverse may provide construction workers with enhanced awareness of their surroundings highlighting underlying and critical infrastructure. This improved understanding of the real world may minimise workplace accidents. A builder may be digging a hole and unaware of the presence of a pipe or a wire three meters below, or using heavy machinery on a high-rise building without noticing what those below them are doing. AR could assist with these hazardous scenarios by placing the objects closer and overlaying the schematics on the ground (Côté and Mercier 2018; Van Son et al. 2018).

Fig. 16.1 X-ray Vision Fiction to Reality. An illustration showing the difference between the fictional application of X-ray vision and the real application of X-ray vision. X-ray Vision Fiction to Reality © 2023 by Bradley Richards is licensed under CC BY 4.0. Full image can be found at: https://live.staticflickr.com/65535/53409661754_a03a59ee8b_h.jpg

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In another scenario, the AR metaverse allows medical practitioners to perform a collaborative surgery procedure from distributed locations (Bajura et al.,1992; Kalkofen et al. 2007; Pratt et al. 2018). Augmenting the surgical procedures with various types of XRV allows people to see objects we are not typically able to see. This has already been accomplished by superimposing CT volumes over some patients directly to help surgeons to repair broken bones (Pratt et al. 2018).

To achieve these feats, we would need to develop Superman like XRV. The fictional superhero can look through any matter to see whatever is on the other side. For instance, not only can Superman look through a wall to see what is on the other side, he can also view inside someone's body and see their bones and organs. Unlike real X-rays, Superman is not hindered by density and can perceive the object's exact location in reality (Pittenger 1983). This is the goal of Augmented Reality enabled XRV (Avery et al. 2009; Bajura et al. 1992).

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15.1.1 X-ray Vision to Augmented X-ray Vision

The public interest in XRV has been created through popular culture and depictions in several science-fiction movies. Furthermore, XRV as a superpower has been a long-held desire (Pittenger 1983). Discovered and named by the German physicist Wilhelm Röentgen in 1895 (Röntgen 1895), X-rays were first used in a medical context for observing internal human structures.

In 1992, an immersive (digital) XRV was first reported when Bajura et al. (1992) visualised a fetus inside a woman's womb using AR during an ultrasound. They found that when you attempted to observe the data from the ultrasound where it was captured, it appeared to be visualised in front of the woman. Consequently, the digital image was not correctly calibrated. The virtual data seemed smaller and as if it were sitting upon the patient. This occurred because the Head Mounted Display (HMD) they were using only displayed objects that were closer to the user and shrinking them rather than making the visualisation look further away. In addition, people do not think they can see through occlusive surfaces, and if they can still see an object clearly, it must be between them and the real world (Bajura et al., 1992).

XRV defines methods that focus on rectifying the depth mismatch caused by the wrong perception of the system on the virtual object being rendered from behind instead of in front of the actual object. Users will receive a similar effect to a Superman-like form of XRV, illustrated in Fig. 15.1 (Bajura et al., 1992; Blum et al., 2012). Over the past 31 years, many techniques have been developed for this concept, but many more challenges remain before XRV can be a ubiquitous tool for the metaverse.

15.1.2 Challenges to Solve in Augmented Realty X-ray Vision (AR XRV)

There are still significant challenges to using AR XRV that need to be overcome to better enable merged physical world views with XRV. Research is ongoing to determine which X-ray visualisations work and which do not in specific environments, technologies, and contexts. Most

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Fig. 15.2 Three images of the Stanford bunny sitting behind a wall. To the left there has been no attempt at X-ray vision except for placing the bunny behind a column. In the center a grid has been placed over the wall to explain to the viewer that the bunny is behind the wall. On the right is highlighting the edge of the bricks using edge detection to indicate that the bunny is behind the wall. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2~~4.0. Image can be found at https://live.staticflickr.com/65535/53409700435_6515bc1748_k.jpg

of the prior research in this area has focused on viability. However, vital questions remain unanswered and are receiving ever-increasing attention.

Challenge 1: Blending the Real and the Virtual Worlds

Current AR headsets that present digital information still struggle to create a seamless blending between the digital and physical real-world information where users can identify the visual information presented on a screen versus that of the physical environment. For example, geometric objects presented on AR headsets struggle to provide precise alignment (errors of less than 1cm) with items in the physical world. As shown in Fig. 15.2, the bunny's position becomes more obvious by closely matching the real world to the X-ray visualisation.

Many AR applications utilise factors like motion parallax and a linear perspective to make objects appear at a seemingly precise distance away from the users. In order to facilitate XRV, the virtual world must be bound to a real-world object enabling the user to perceive both worlds as one, as presented in Fig. 15.2.

Challenge 2: Device Capabilities and User Requirements

Realistic colour representations are challenging on different displays, and as shown in Fig. 15.3, AR further complicates this issue. AR experiences utilise many devices. Unfortunately, each apparatus brings its own problems, such as what colour gambit they can display, the contrast they bring to the real world, how much of their real vision is occluded and the specific configurations of how the virtual and the real worlds are viewed (Erickson et al. 2020). Fig. 15.3 shows the gradual change in colours between a computer display and an OST AR. The OST AR display amplifies the brightness the colours than intended, whereas the VST AR overlay struggles to choose between the foreground and the background colours. The observed changes come from several hardware limitations and user preferences on the mentioned devices and will likely always be treated somewhat differently.

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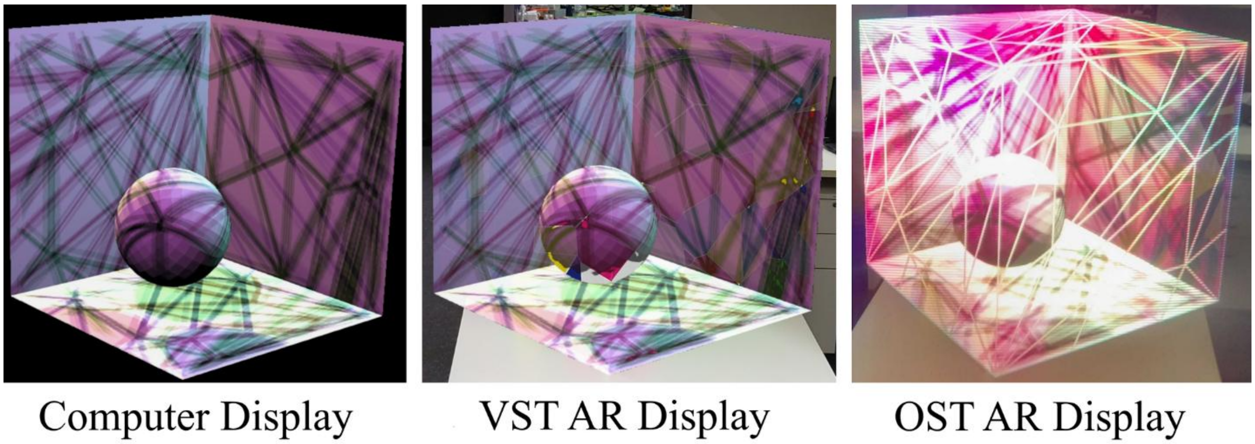

Fig. 15.3 This figure shows images from a computer monitor, an AR overlaid image, and the HoloLens2's display directly, featuring a Box with a wireframe version of X-ray vision that is able to cast a shadow over the unseen area based on the X-ray vision effect. A set of red, blue and green lights is directed at this object showing almost the full color gambit. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2~~4.0. The image can be found at https://live.staticflickr.com/65535/53409436738_a226e84a0b_k.jpg

Challenge 3: Depth Planes

The majority of displays only have a single depth plane or a point of focus. This means there would be only an element in the focus when there is a certain distance from the user. A simple example of this is that one cannot watch a TV if one is trying to look past it. This is caused by the interplay of Accommodation and Convergence Depth cues (Cutting and Vishton 1995), shown in Fig. 15.8. In the real world, AR devices replicate human eyes focus to a point but cannot completely correct themselves for seeing an object further away. Not only does this impair depth perception, but it also impacts the methods that allow the interactions with the displays as the eye movements have to focus differently than they would naturally in reality.

15.1.2.1 Challenge 4: When Does a User Want to Look Through a Wall?

XRV is great, but when it should and should not be used is difficult to tell. Superman can look through a human body to the level that he wishes, but this is not the case for a normal human (Pittenger, 1983). Mankind does not have this ability, and while AR is utilised to look left and right and up and down, the technology cannot determine when we want to peer forward and backward. As seen in Fig. 15.4, our accommodation is fixed at a single point in AR, disabling the ability to focus on something nearby or far away.

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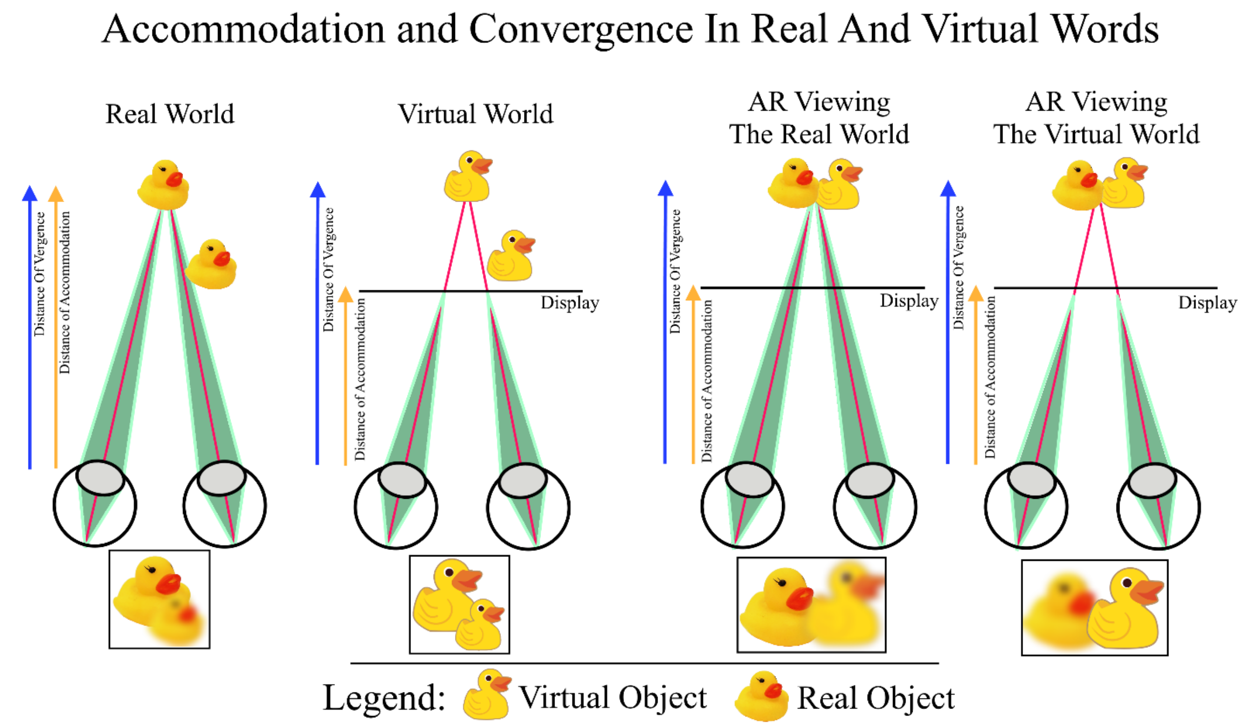

Fig 15.4: A description of how convergence and accommodation work in the real world and using Mixed Reality. It consists of 4 diagrams showing how accommodation and convergence work together to better sight. With a example image below each diagram. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2~~4.0. The image can be found at https://live.staticflickr.com/65535/53408334727_efb9e12b64_h.jpg

15.2 Methodology: A Systemic Style Literature Review of Augmented X-ray Vision (XRV)

This literature review was inspired by the PRIMA 2020 SRC (Page et al. 2021) protocols checklist. It utilised five databases: ACM Digital Library[1], IEEE Xplore[2], Pub Med[3], Web of Science[4], and Scopus[5] using the search terms:

“("X-ray vision" OR "X-ray visualisation" OR ("occlusion" AND "perception") OR (Visualization AND X-ray) OR "see-through vision" OR "Ghosted Views" OR "Augmented reality X-ray") AND ("AR" OR "Augmented Reality" OR "Mixed Reality")”

[1] https://dl.acm.org/
[2] https://ieeexplore.ieee.org/
[3] https://pubmed.ncbi.nlm.nih.gov/
[4] https://www.webofscience.com/
[5] https://www.scopus.com/

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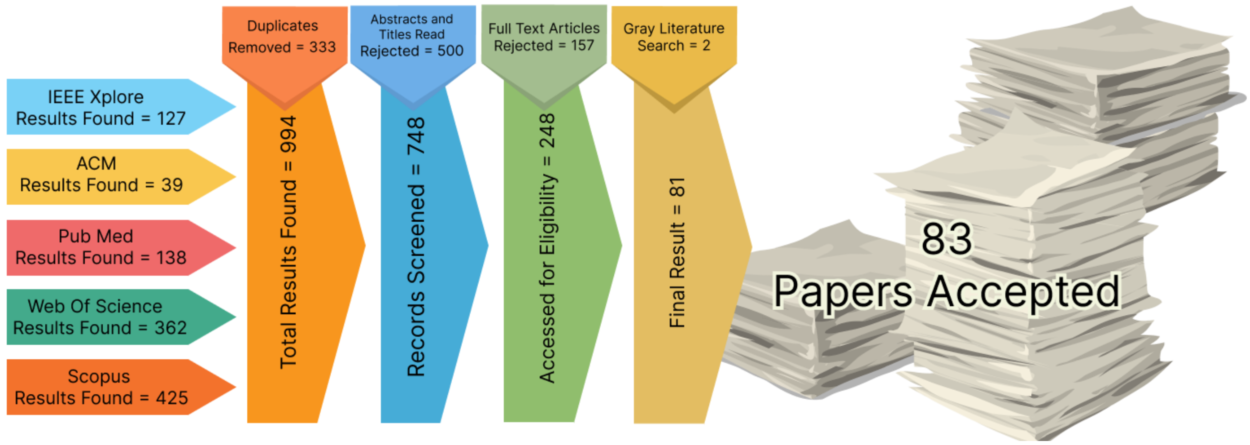

Fig. 16.5 Protocol Utilized for this Literature Review with the matching results.

These terms were filtered by the paper's Abstract, Title, and Keywords. To find grey literature, papers cited by more than five papers were also considered for entry into this database (2 papers found and accepted). For a paper to be accepted, it needed to meet the eligibility criteria outlined below. The process and results of this review as depicted in Fig. 16.5.

All papers in this review needed to meet the following criteria:

- X-ray vision (XRV) needed to be explored in the research, placing virtual objects behind real-world objects.
- Mixed Reality Technologies other than VR must have been used.
- Papers that simply superimposed data over the real world and papers that did not focus on making the content appear on the other side of or within the real-world object were not included.
- Studies included in multiple papers were only recorded once all papers that highlighted the same research had been included in this review, as the content between both articles provides different amounts of information.
- If the focus on XRV was light compared to other study elements and two or more reviewers agreed on it, then the work would not be included in favour of more focused research.

These criteria allowed us to ensure that the X-ray visualisation was more than superimposing a medical image onto a human subject. We removed any paper that did not utilise Augmented Reality. This meant that some papers that utilised Virtual Reality technologies to test Augmented Reality in a completely virtual environment were not included, as XRV was not a focus of the paper.

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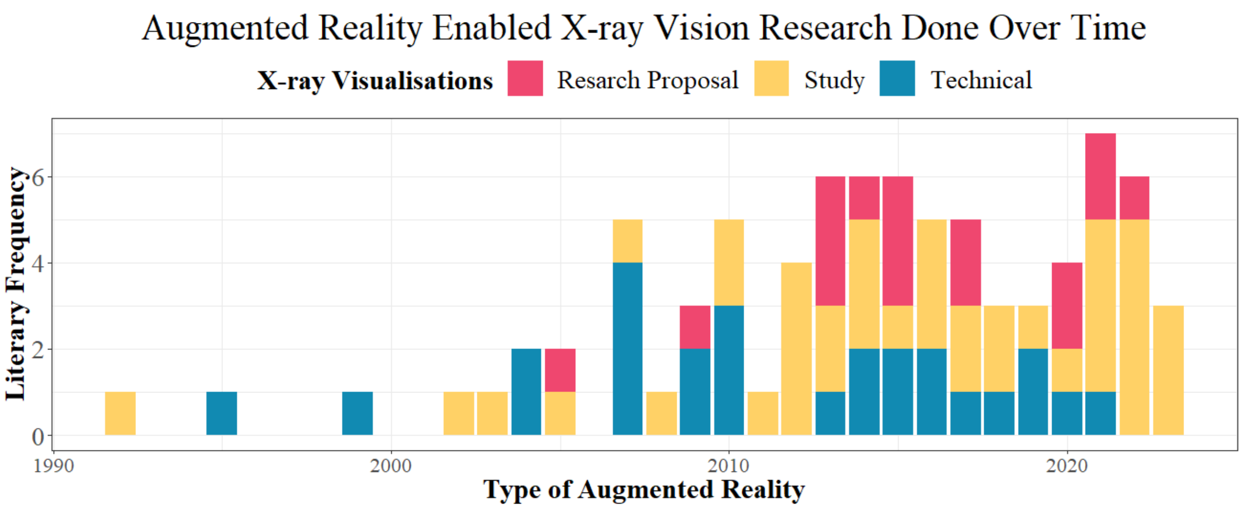

Fig. 15.6: A bar graph showing representing the amount of papers that were published in X-ray vision each categorized by the type of research they have done. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2.0. This image can be found at https://live.staticflickr.com/65535/53411130141_1bc1e66140_b.jpg~~4.0.

15.3 Observations

This section presents the complete findings of all the X-ray vision (XRV) papers we found as of the 30th of October 2023. The various devices that XRV techniques have been used on are discussed, along with the developed techniques for XRV, their functional mechanism, and the research focus. Following this, we look at how each user study was conducted, and the parameters utilised for the various experiments.

Of all the selected papers that were longer than two pages, we found 27 Technical papers (3 of which also included a case study) and 29 papers that presented a user study. Three demonstrations have been showcased at conferences. Ten short papers have highlighted various research proposals, many of which detail pilot studies for some of the 29 user studies.

Every task that required its own set of results was considered a study, and if no results were published for a given study, it was not included in our analysis.

Research proposals have become more frequent than technical papers in recent times. Papers prior to 2010 tended to be largely technical. Over the last decade or more, we have learned more about how this effect works by focusing on user studies and research proposals. This is detailed in Fig. 15.6, which illustrates the steady maturation of the field, moving away from novel techniques to understanding their effects and how they can be improved.

15.3.1 Applications of X-ray Vision (XRV) in the Metaverse

Fig. 16.4 indicates the prevalence of XRV applications in different domains. While AR technologies, in general, are increasingly being used to support communication, social interactions, business, and marketing use cases, the application of XRV focuses on specific domains where the visualisation of internal structures and hidden information are important. XRV technologies feature prominently in the medical, construction and maintenance domains. In addition, generic techniques may be applicable in multiple domains, as shown in the Generic category in Fig. 16.7. Security and Navigation each presented several examples, while few examples of XRV were encountered in the remaining application areas.

All of the generic papers tend to present important information relating to fundamental aspects/tasks/challenges that can be applied to a wide range of situations. These include navigating through one's home or office, interacting with robots, determining the distance between an object and a user, or simply proving how to place items in a location. The findings of these papers are relevant to many fields. These findings span a diverse range of novel research with the development of visualisations primarily tailored for these purposes, offering foundational guidance for domain-specific papers(Kalkofen et al. 2007; Kitajima et al. 2015; Otsuki et al. 2015; Sandor et al. 2010).

In the medical domain, X-ray Vision (XRV) integration supports in-situ diagnostic capabilities and surgical activities. XRV allows medical professionals to visualise virtual information related to internal structures, such as bones, organs, and tissues, in real-time overlays onto a patient's body during examinations or procedures (Bichlmeier et al. 2007; Blum et al. 2012; Erat et al. 2013; Habert et al. 2015; Lerotic et al. 2007). XRV can enhance diagnostic accuracy by

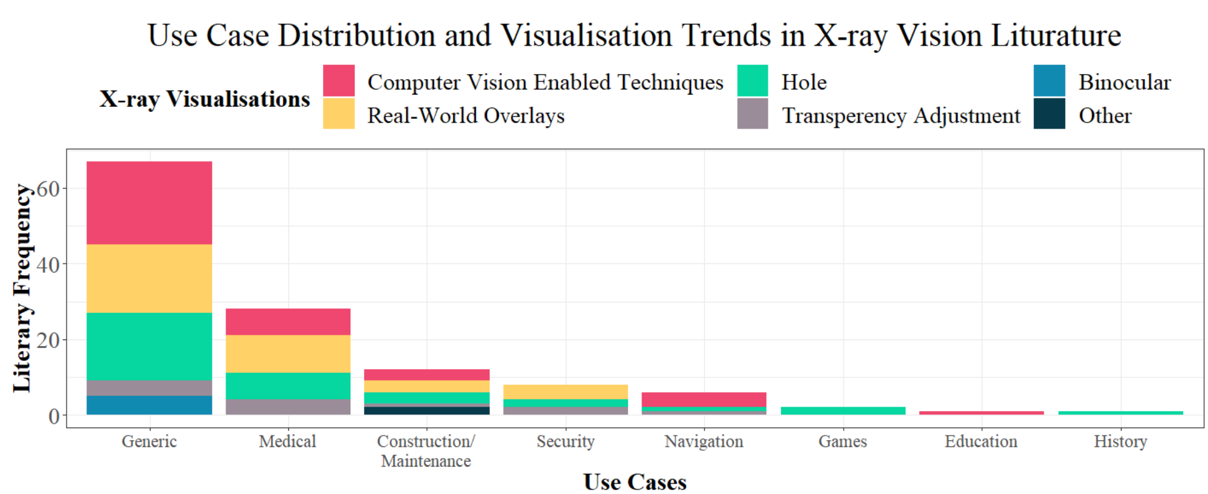

Fig. 15.7: A bar chart representing the amount various amount of research aimed at a given application of X-ray vision. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2.0. This image can be found at https://live.staticflickr.com/65535/53410215847_af0cf70ddb_z.jpg~~4.0. This Image can be found at

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providing an immediate, three-dimensional view of anatomical structures, aiding in identifying abnormalities or subtle variations (Bichlmeier et al. 2007; Blum et al. 2012).

During surgeries, XRV could potentially enable surgeons to navigate complex anatomies, guiding them to target specific areas and confidently perform invasive procedures. The works encountered in the literature present technologies validated by case studies demonstrating how such solutions could be adopted in diagnostic and interventional aspects of healthcare. However, further work is needed to mature the technology and align it with clinical requirements and regulations to enable the clinical use of such technologies on a routine basis.

In construction and maintenance, XRV enables construction professionals to see through physical structures, facilitating a comprehensive understanding of internal structure and integrity and identifying potential issues that may be otherwise hidden. Such capability can support building inspections, allowing real-time visualisation of hidden structural elements, electrical wiring, and plumbing systems(Becher et al. 2021; Eren and Balcisoy 2018; Muthalif et al. 2022). Moreover, it can help pinpoint areas requiring attention within existing structures. By providing a transparent view into the inner workings of buildings, XRV enhances construction quality control, accelerates maintenance procedures, and contributes to the safety of built environments (Feiner et al. 1995; Liu and Seipel 2018).

In the security industry, the XRV can augment situational awareness and reveal potential security threats. XRV has the potential to reveal persons or objects obscured by walls and other objects, support situational awareness by melding real-time surveillance information with the security personnel's view of the immediate environment, and identify concealed items. Although use cases in the security domain may benefit from the ability afforded by XRV to see through and around physical objects, relatively few user studies of such applications have been found in the literature. A possible explanation may be that such applications are commercially sensitive and, hence not published in the academic literature (Kameda et al. 2004; Livingston et al. 2005; Ohta et al. 2010; Phillips et al. 2020; Tsuda et al. 2005).

For spatial and location-based activities, XRV has been proposed to support the user's ability to see beyond their immediate physical environment, enabling users to see inside and through built structures. Such an extended view has been proposed to aid navigation tasks. These include showing navigational cues on a road that can respond to depth cues (Yasuda and Ohama 2012), looking through buildings to understand what is on the other side to give an increased sense of space (Dey et al. 2011; Maia et al. 2016), and even navigational experiences closer to "time travel" such as sight of the historic appearance of modern cities in situ (Yamamoto and L 2014). The same approach could be used to transplant virtual structures defined in a metaverse into the physical environment to create a hybrid space or assess proposed changes before the physical environment is altered.

Some areas that have received no or little attention, as depicted in Fig. 15.7 are topics like baggage screening and education. Santos et al. (2015) have produced some work looking into the

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effect that XRV has when educating school children but did not find any major findings regarding XRV itself. Rather, they found that AR did make students more excited about learning (Santos et al. 2015). There are likely many findings where the crossroads of XRV over 3D models, and education which could be used to educate students. However, to date, this is still an open field.

XRV research in games and entertainment appears to be rare according to the results shown in Fig. 15.7. This is likely because there is a lot of overlap between these fields and generic topics. However, several augmented reality video games like Microsoft’s RoboRaid (Microsoft 2016) and Dr Grordbort's Invaders do exist in the space. Gaming strives to take XRV into new territories and finds different methods of interacting with virtual world. This lends itself to aiding usability, but the field still has a lot to learn about how XRV can and should be used.

15.3.2 X-Ray Vision Techniques

Various approaches have been employed to create X-ray Vision (XRV) techniques. Most of these approaches utilise a form of partial occlusion, as this is a very powerful depth perception cue, while other techniques rely on other depth cues to allow the user to look through real-world objects. However, in order for these effects to work in a true AR metaverse, there should be an understanding of the roles of X-ray techniques in different scenarios (Fig. 15.7) and on separate devices (Fig. 15.9 and 15.16).

The following section will detail four groups of X-ray visualisation methods at a high level. There are many variations of these effects and where appropriate, very similar effects have been categorised together in this section for brevity. The XRV effects that do not belong to any of these groupings are filtered into the “other” condition in Fig. 15.7 (Eren et al. 2013; Muthalif et al. 2022).

15.3.2.1 X-ray Vision Effects

The main way to create an X-ray vision (XRV) effect is to utilise a visualisation that clearly anchors the real world to the virtual world, providing some depth indication. This is generally by using occlusion as presented it is the strongest depth cue in Fig. 15.8. However, Fig 15.8 showcases another 7 depth cues XRV can be achieved by utilising other depth cues such as accommodation convergence, relative scale, and density (Cutting and Vishton 1995).

Auxiliary Augmentation utilises the relationship between two different objects employing the depth cues of relative size and density and the effect of motion (Clarke et al. 2022). Using another occlusive XRV technique on one object provides enough information to inform the user of the position of the other object (Clarke et al. 2022; Kytö et al. 2013).

Vengeance-based XRV is designed to have people change and move their focus away from the foreground to focus on the background image. This method tends to simulate binocular distortion. By tracking a user's eyes, it is possible to tell when they are trying to look past an

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object. This can advise what should and should not be kept in view whilst creating and placing objects approximately where the users expect them to be. This effect seems more effective when used in conjunction with other X-ray visualisations (Kitajima et al. 2015).

15.3.2.2 Transparency Based X-ray Visualizations

One of the simplest forms of XRV used is the ability to adjust the transparency of a part of an image (as seen in Fig. 15.13). By configuring the transparency within reference to the current view, a user can be given the impression that the object is either in the foreground or the transparency may be low enough that they feel as if they are looking inside of the object. This form of XRV is typically called *Alpha Blending*.

Three papers (Kameda et al. 2004; Ohta et al. 2010; Tsuda et al. 2005) have explored *Alpha Blending* and its possible applications when adapting it to security cameras, allowing for one line of sight to combine the information of several security camera's at once. Rather than having each security camera link to a single screen, their XRV method makes the foreground object more transparent, presenting the content behind them. This technique provides better information and insight when looking through buildings. Tsuda et al. (2005) did find that this technique tends to work best when paired with another visualisation technique. The inverse of this has also been used as a visualisation technique by making the virtual object less visible. This approach can help the user focus on the real world using the AR as a guide. This method is commonly uses a monoscopic VST AR display (see Fig. 15.9) in medicine where users want to view the X-ray visualisation as a guide while still being able to concentrate on their work (De Paolis and De Luca 2019; Erat et al. 2013; Pauly et al. 2012).

15.3.2.3 Hole in the World-Based X-ray Visualizations

Hole-based X-ray visualisations focus on creating a sense of partial occlusion by allowing a user to look through an object. The right side of Fig. 15.9 depicts the flexibility of this visualization, showing it can be used on almost any AR device. Some of these methods use partial occlusion by simply having a user look through a 2D window (Fig. 15.10 virtual window), while others use tunnelling (Avery et al. 2009) or cutaways (De Paolis and De Luca 2019; Feiner and Seligmann 1992)**.** The most popular of all these techniques is to create an open box for people to look into, allowing people to get an accurate sense of how far away in a real-life object the virtual object is placed. This provides the impression that the object is inside of a real-life object.

Although the hole in the world visualisations tend to work quite effectively, they have a few limitations. Firstly, the visualisation needs to be in a static position. It cannot rotate or change size relative to the user's motions. This means that the hole should not react to user movement. The user could, however, choose to make the hole larger or smaller, without breaking the effect. There is a limited field of view into the hole. Although the limited view creates the XRV effect,

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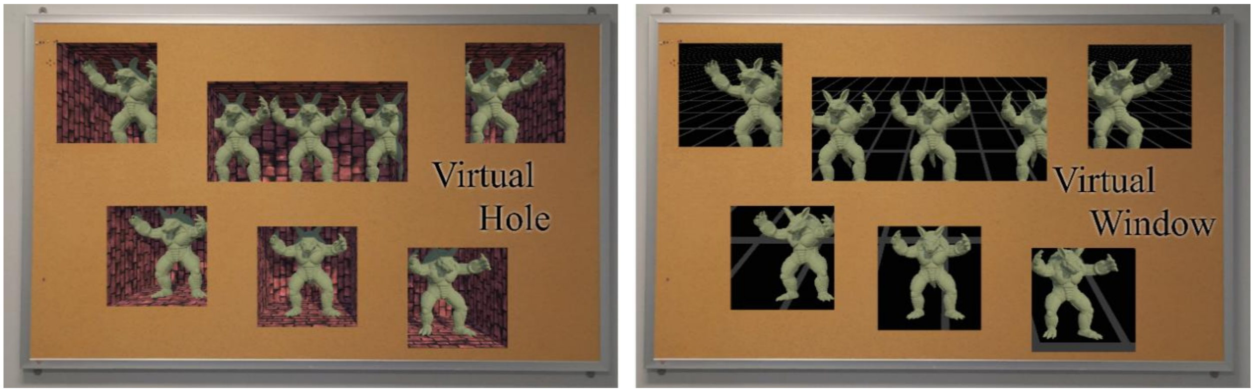

Fig. 15.8: All images show an armadillo sitting at the same position behind a corkboard in AR with the same orientation. On the left are virtual holes, and on the right are virtual windows. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2~~2.0. This image can be found at https://live.staticflickr.com/65535/53409746615_e8299b2fd1_k.jpg

it restricts the view the user may have of the data. One large advantage this type of XRV method is that it can be viewed using any display.

The *Virtual Hole (or Virtual Box)* X-ray visualisation was the first type of XRV to be implemented and was designed by Bajura et al. (1992) can be seen in Fig. 15.10. To this day, it is still one of the most used X-ray visualisations and is still being heavily researched in modern studies (Blum et al. 2012; De Paolis and De Luca 2019; Phillips et al. 2021). *Virtual holes* have been found to provide a relationship between virtual objects and the real world. Kytö et al. (2014) found that users could better determine distance if they had a partially occluded object in the scene for users to use as a reference.

Cutaways and *Tunnelling* present a hole through an object, revealing an object on the other side of the object (Avery et al. 2009; Feiner and Seligmann 1992). Both these techniques can be seen in Fig. 15.11. This tends to appear as a box with no back. These visualisations focus more on indicating where the data is in the real world rather than giving the user a better sense of depth when looking through a particular piece of data.

Virtual Windows (seen in Fig. 15.10) are some of the most straightforward X-ray visualisations, showing the user a perspective of a 2D hole in the wall. These are sometimes presented as a crack in the wall or will have a slight frame. These windows can range from literal holes in the walls to merging with the surface of a given material (Bichlmeier et al. 2007; Guo et al. 2022). Contextual Anatomic Mimesis is one form of these windows designed for working with medical applications autonomously. It gradually moves from having the appearance of skin to looking more like the virtual content while still presenting a slight overlay based on the roughness of the skin (Bichlmeier et al. 2007). Research by Martin-Gomez et al.(2021) has shown a significant

Fig. 15.9: Left: Cutaway through a wall to a storeroom (front) and Tunneling (rear) though another room to the outside. Left: A directly rendered volume of a hierarchical set of spheres utilizing X-ray visualisation that uses a silhouette/Halo X-ray visualization. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2~~2.0. This image can be found at https://live.staticflickr.com/65535/53408401222_25fccf6553_k.jpg

improvement to this effect when paired with another effect to help represent the depth of an object.

15.3.2.4 Real-World Overlays

The most common way of providing XRV effects on Fig. 15.7’s left-side graph is to represent the physical environment using a virtual pattern. This is typically done in two ways. One way is to place a pattern on the ground, allowing users to retain some knowledge of depth by using a constant geometric cue (Gruenefeld et al. 2020; Tsuda et al. 2005). The other method utilises overlaying the real-world object with a pattern of some sort. The second method tends to be used when viewing virtual objects in stereoscopic displays as it requires a level of geometric saliency to be perceptible. Binocular disparities are generally required for these types of visualisations to function (Otsuki et al. 2015).

Fig. 15.12 illustrates some of the forms that real world overlays can take for example overlaying *grids* (Becher et al. 2021; Heinrich et al. 2022; Heinrich, Joeres, et al. 2019; Johnson et al. 2014), *Wireframes* (Y. Chen et al. 2020; Clarke et al. 2022; Gruenefeld et al. 2020; Tsuda et al. 2005) and *Random Dots* (Ghasemi et al. 2017; Otsuki et al. 2015). All of these effects are designed to utilise partial occlusion to highlight the shape of the object and to help the user understand the orientation from the wall. This gives the user a better comprehension of the distance between themselves and the objects they are looking into.

Random dot is another way of expressing more occlusion than other geometric pattern effects would typically employ (Ghasemi et al. 2017; Otsuki et al. 2015). This effect provides a partial sense of occlusion by providing a semi-occlusive layer over real-world objects (Otsuki et al. 2015). This effect is one of the least computationally expensive but requires an immersive

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environment. Highlighting various pixels on the surface of objects provides a stereoscopic effect of occlusion for the user and should technically allow for a better sense of depth. However, this visualisation has yet to be extensively tested on abstractly shaped objects.

Halo and the *Silhouette* (shown in Fig. 15.11) XRV effects present a bright light around the edges of the object of interest and uses alpha blending to communicate depth (Ozgur et al. 2017). The halo has a set size, leveraging the depth perception cue of relative size. This XRV effect is unique for the lack of occlusion it provides, making it effective for surgical situations. It has been tested using a monoscopic display in a study designed for minimally invasive surgeries. It can also exploit a colour-based effect, applying visual language to communicate depth to the user.

15.3.2.5 Computer Vision-Enabled Techniques

In computer vision, there are several methods of highlighting salient features in an image. This is normally done by highlighting various salient factors within an image. Fig. 15.9's Left side graphs communicate that these techniques are commonly used on monoscopic devices as they provide a good sense of where an object is positioned relative to another in 2D. To this date, the results lack the performance of these techniques in stereo, with most of the publications we found in this space either being demos or research proposals (Clarke 2021; Phillips et al. 2021; Rompapas et al. 2014). Clarke et al. (2022) present findings that indicate that these techniques appear to have a negative effect on stereo OST AR devices, however, further research is needed in order to confirm these findings.

Edge-based X-ray visualisations (depicted in Fig. 15.13) identify areas in the user's view that contrast highly between neighbouring pixels and highlight them. This visualisation creates a predictable method for highlighting areas on an image (given that the surface has a high level of

Fig. 15.10: Wireframe, Random Dot and Grid X-ray visualisation over colourful patterned box with a virtual cube, sphere icosahedron and a Stanford bunny rendered inside. The image was taken using the HoloLens' screen view. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2~~2.0. This image can be found at https://live.staticflickr.com/65535/53409573485_3425810730_k.jpg

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Fig. 15.1 X-ray vision showing alpha blending, Saliency and Edge based Visualizations (Shown left to right) looking through a building. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2~~2.0. This image can be found at https://live.staticflickr.com/65535/53409308576_d8dcddf41a_k.jpg

contrast) and makes it a popular way of showcasing XRV on a monoscopic AR device (Avery et al. 2009; J. Chen et al. 2010; Dey and Sandor 2014; Kalkofen et al. 2007; Sandor et al. 2010). By highlighting the edges of an object, we can create the appearance that an object is behind the object either through partial occlusion (Avery et al. 2009; Kalkofen et al. 2007) or by cutting out elements of the X-rayed object (Dey et al. 2012; Dey and Sandor 2014).

Saliency highlights areas of the real world that are likely to be of interest and makes the areas that are unlikely to less apparent. Fig. 15.13 shows one method of using saliency as an X-ray visualisation. The visualisation technique can vary between implementations because it can be done algorithmically or by training an AI model to detect the features a human is more or less likely to look at (Cong et al. 2019; Sandor et al. 2010). A user could naturally peer through objects using the saliency method, given that the camera could find some salient and non-salient areas of the image(Sandor et al. 2010). However, determining what a user considers salient is often challenging (Clarke et al. 2022). Saliency has been used for both Spatial Augmented Reality (SAR) and VSTAR devices, and some papers have suggested that it is more pleasing than other forms of XRV.

Ghosting has a similar effect to *Saliency,* and focuses on allowing artistic approaches to partial occlusion (Ren and Malik 2003; Zollmann et al. 2010). *Adaptive Ghosting* is an extension of these effects, which combines the salient effect of ghosting and edge-based XRV effects. By adapting the Ghosting technique to the current environment it less varied when viewing it from different directions (Kalkofen et al. 2013).

15.4 Devices

A metaverse should not be restricted to a collection of augmented reality devices like phones and head-mounted displays but can also extend to systems of static screens in the real world that react to gesture-like commands (S. M. Park and Kim 2022). In this field, many different displays have been used to create different display technologies from varying perspectives. In Fig. 15.14 and Fig.15.15, we have categorised devices based on their use. Head-mounted displays used as display devices are grouped. Portable screens like phones and tablets, larger screens, and magic

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mirrors fall under the 'Screens' category. Additionally, three user studies utilised Images and Spatial Augmented Reality (SAR).

X-ray vision (XRV) systems can be supported by various display devices, including mobile phones, head-mounted displays, computer screens, and projectors (Kim et al. 2018). Devices range from traditional computer screens and mobile personal devices, head-mounted displays to projectors. Most earlier devices can only accommodate monocular vision, while recent head-mounted displays can support stereoscopic vision. Fig. 15.14 shows that the choice of technology is often a result of technological advances and emerging products. It can be observed that mobile screen-based displays were most popular following the release of powerful mobile phones in 2007, underpinned by emerging computer vision techniques for tracking and the generation of visualisations. Similarly, stereoscopic head-mounted displays gained popularity because of increased capabilities, technology maturity, and general availability in recent years.

The widely used Microsoft HoloLens 1 and 2 in XRV research stand out for their advanced display tech and gesture recognition making it a useful device for security and medical operations (illustrated in Fig. 15.15). HMD's shine in medical settings, offering a sterile work environment. Medical applications use screens for remote interactions, like controlling robotic arms in minimally invasive surgery. In contrast, the construction and maintenance industries employ a diverse array of devices due to their varied environments.

SAR techniques are a relatively novel addition to XRV, where only a few exemplars have been published in Fig 15.14. In contrast to head-mounted or fixed display devices, SAR technologies can augment the physical environment in situ without obstructing the user's field of view. However, accurate calibration and tracking of the user's vantage point are essential for high-

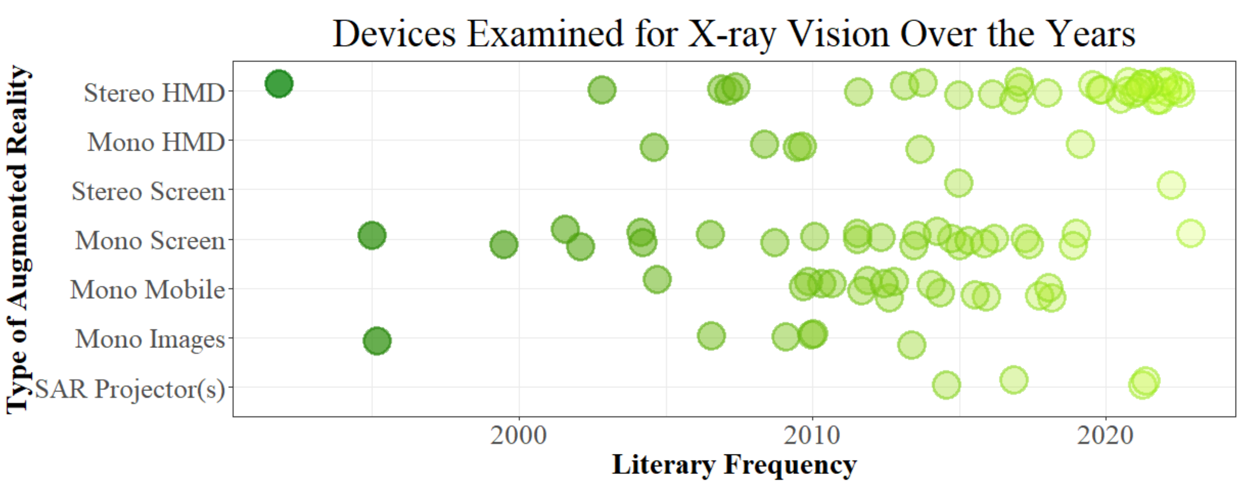

Fig. 15.2 A plot showing various devices found in the literature over the years. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2.0. This image can be found at https://live.staticflickr.com/65535/53410218202_25e69e5527_b.jpg~~4.0.

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precision XRV. Generally, XRV SAR-based systems are uncommon but have been done in medical settings and settings where the user is relatively stationary and needs an unobscured vision(Heinrich, Bornemann, et al. 2019).

15.4.1.1 Sensors Utilized

The information used in XRV applications may possess different characteristics about the nature of the data, its temporal characteristics, and realism. Three-dimensional models, point clouds, video feeds and photos, medical data, and depth maps are examples of the diversity of data visualised in XRV. Moreover, one can distinguish static information which, remains unchanged for a task, and dynamic information which, may change during a task. Finally, the degree of realism of the data can vary.

Fig. 15.16 illustrates that static information prevails as the most common virtual element in XRV, constituting 65% of the 54 papers examined. Examples include 3D models, medical images, and building schematics, predominantly found in medical, construction and maintenance domains. Virtual objects range from simple geometric shapes to intricate representations of real objects (Becher et al. 2021; Eren and Balcisoy 2018; Eren et al. 2013; Muthalif et al. 2022; Zollmann et al. 2014).

Dynamic data, as depicted in Fig. 15.16, often comprises video feeds from static or mobile cameras. This technique, capturing information from multiple perspectives, enables users to perceive distant or hidden details while viewing the actual environment simultaneously. Security and robotic system control applications benefit from these methods (Erat et al. 2018; Phillips et

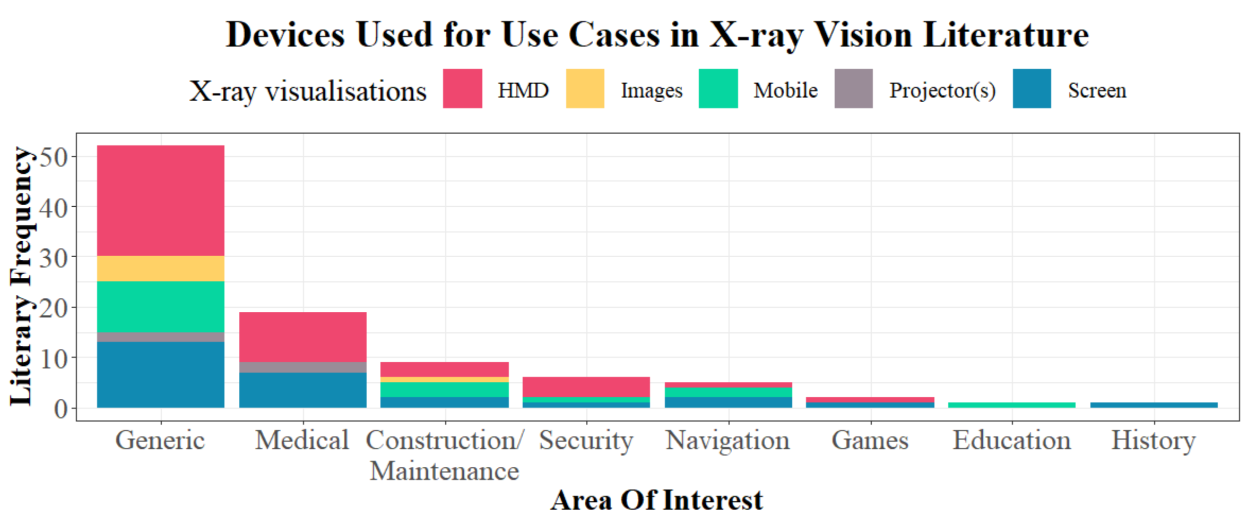

Fig 15.4: A graph showing the preference of various AR input devices for given use cases based on the literature found. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY 4.0.

Fig 16.3 A graph showing the preference of various AR input devices for given fields based on the literature found. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY 2.0. This image can be found at https://live.staticflickr.com/65535/53411459489_6ff467ba98_b.jpg

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al. 2021). The real-time delivery of camera-captured information mirrors the real world, with non-dynamic data commonly used in construction to model underground pipes. This addresses the challenge of communicating the position of underground structures to end users (Becher et al. 2021; Eren and Balcisoy 2018; Eren et al. 2013; Muthalif et al. 2022; Zollmann et al. 2014) Notably, XRV experiments in construction consistently utilize simulated data, aiming to replicate real-world scenarios.

Most of the research that utilises live recordings in this review employed cameras or medical equipment (shown in Fig. 15.16). No studies were found that visualised radar and other sensor data in a 3D manner to create an XRV effect—limiting the types of visualisations that people were viewing. Techniques like photogrammetry were not found either. This would lead us to believe that XRV, to this point, has mainly focused on showing visualising the known world to the user rather than looking into having the system visualise a black box.

15.4.2 Research Exploring X-ray Vision (XVR)

Creating an effective XRV solution for a task requires careful design, construction, and validation of the system to discover an appropriate balance among the possible solutions aiming to address the challenges related to AR and XRV technologies. Research studies investigating depth perception, spatial awareness, interaction techniques, and usability of XRV systems can be

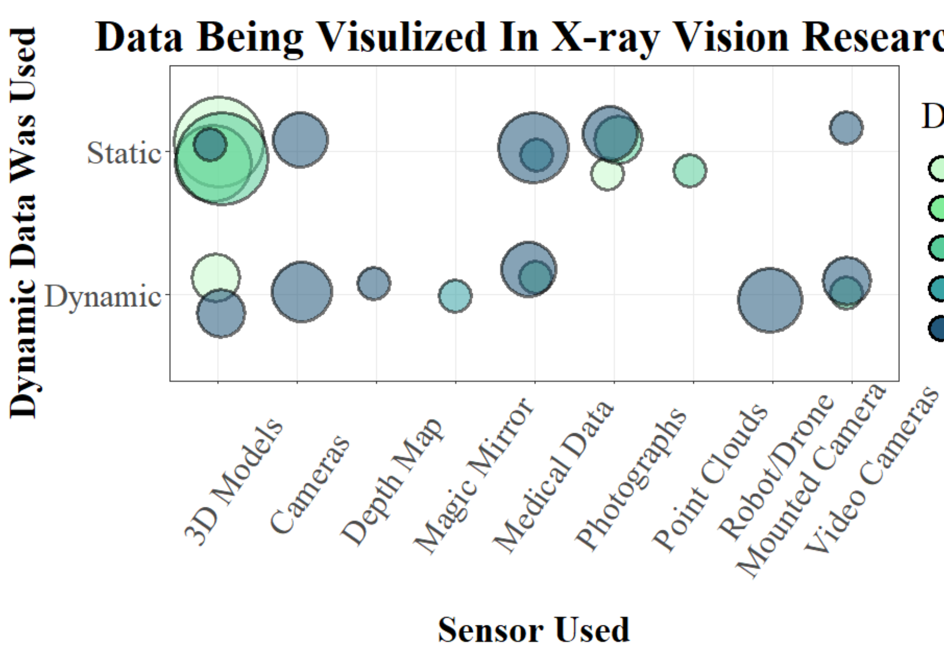

Fig 15.14: A bubble plot detailing the sensors used to collect the x-rayable content use of static and dynamic background material located behind/inside of the X-rayrable image. Image provided by authors.

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found in the literature. Fig. 15.17 shows the prevalence of the different topics in the surveyed literature.

The effectiveness of visualisations and interactions for a given task may depend on the distance of the physical and virtual object(s) from the user. The human eye's ability to perceive depth and fine detail may vary as a function of distance, and a human's reach to manipulate physical (and sometimes virtual) objects is constrained by human anatomy. Perception and interaction have been studied in several settings, ranging from within arms' reach distance to scenarios where distant objects are interrogated and manipulated. Depth perception AR and VR tend to look at methods of improving the user's sense of space in an environment. Research into the depth perception of XRV focuses on how to influence the impact on depth perception when looking through an object.

Depth perception and perception more broadly have received considerable attention in the research community since accurate depth perception is vital for XRV user experience. In most of the research done regarding depth perception in XRV is related to fixing the depth/distance offset

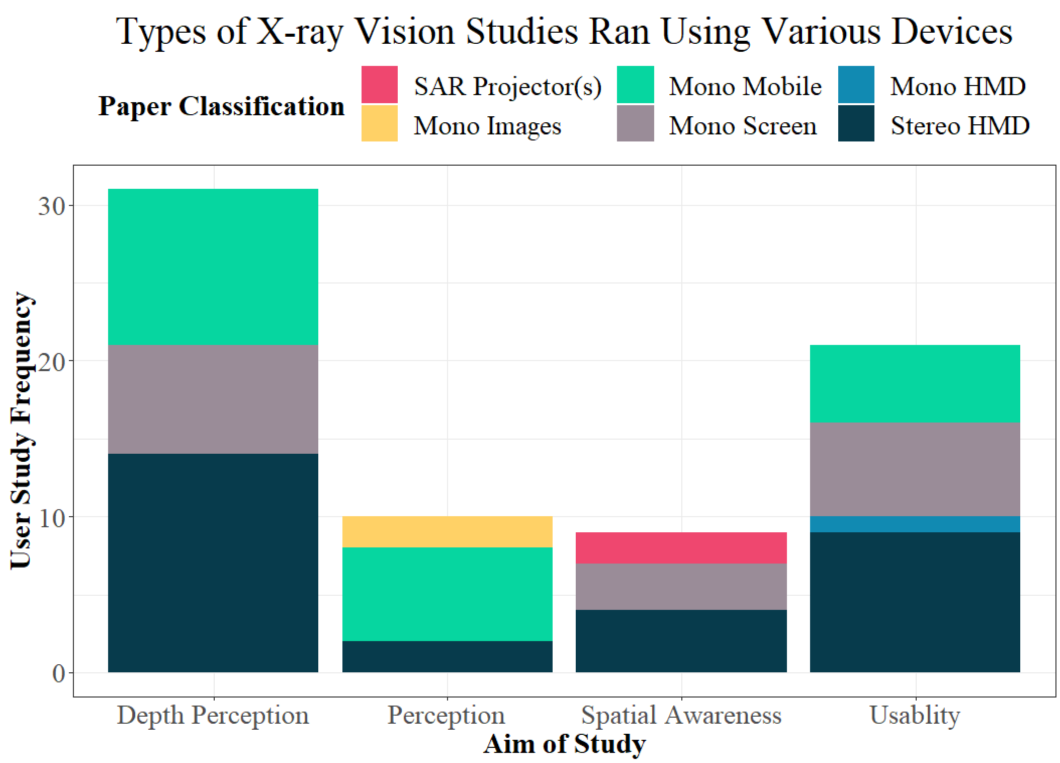

Fig 15.5 A plot showing the different studies that have been ran using X-ray vision research and the types of research done with them. Image provided by authors. This work © 2023 by Thomas Clarke is licensed under CC BY ~~2.0. This image can be found at https://live.staticflickr.com/65535/53411128756_208d496db4_b.jpg~~4.0.

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caused by trying to place a virtual object on the other side of a real-world object (Furmanski et al. 2002; Ghasemi et al. 2017; Sandor et al. 2010). This makes the work in this field done with depth perception different to other forms of research on depth perception. Some works are looking into methods to enhance the depth perception of visualisation (Fischer et al. 2023; Martin-Gomez et al. 2021). The major finding that seems prevalent in this field is that partial occlusion is an effective tool to improve depth perception.

Spatial awareness is concerned with a user's understanding of and ability to operate effectively in a physical environment augmented through XRV. Findings in this field generally look at the impacts of using these visualisations have on aspects like the general placement of an object or attempts to navigate themselves around a foreign environment (Clarke et al. 2022; Heinrich et al. 2021; Li et al. 2016). XRV can orient people using exterior landmarks across large buildings (Dey et al. 2011).

Effective mechanisms to interact with and control an XRV visualisation are essential to the effectiveness and usability of an XRV system. Making usability the second largest topic of research in XRV. Creating interaction mechanisms that cater to the combined characteristics of physical and virtual elements in XRV can be challenging. Interaction mechanisms, including gestures, button and menu commands, and eye tracking, have been proposed in the literature (Liao et al. 2023; Wang et al. 2022a). However, further investigation of the characteristics and trade-offs of candidate interaction mechanisms is needed to obtain comprehensive knowledge about the qualities and trade-offs associated with each visualisation and interaction mechanism in a variety of XRV settings.

15.5 Discussion

We believe AR technologies that enable X-ray vision (XRV) will continue evolving with additional capabilities that will assist with everyday activities in diverse areas. Visualisations will also play an important role in presenting digital information with a seamless connection between the virtual and physical real-world spaces. A recent example of technological advancement is demonstrated on the Magic Leap 2[1], which provides two vision-focus planes and the ability to darken pixels, making it possible to show higher quality of occlusion on OST AR devices. Recent research reveals that the future is bright in this area as advances in eye tracking allow for a much higher level of calibration than before (Arefin et al. 2024).

There are existing examples of XRV that allow people to look through physical objects in the real world using AR devices. In this paper, we have grouped the techniques currently used to achieve this capability into five different categories individually to each been researched, and there is still much to learn in this space. Most of the papers on XRV focus on utilising a

[1] https://www.magicleap.com/magic-leap-2

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visualisation that partial occlusion as a method to improve the merging of the physical and virtual information. It is possible there could be many other methods to enhance XRV techniques with better precision. Also, the effect of visual saliency to improve X-ray visualisations seems rather evident with Ghosting, Edge, and other Saliency X-ray visualisations, given their positive results and popularity in the literature.

Currently, there is a reasonable understanding of how the various X-ray visualisations work, especially on mobile devices (Dey and Sandor 2014; Santos et al. 2016). We understand the techniques required to provide a user with the perceived ability to look through an object in AR (Ghasemi et al. 2017). Several open research challenges with XRV are seeking to find methods to improve the precision, accuracy and depth perception or its presentation.

Currently, XRV researchers are exploring how to make XRV perform as well as our natural vision. This includes challenges like improving depth and spatial perception (Clarke et al. 2022; Gruenefeld et al. 2020; Martin-Gomez et al. 2021) and the creation of new interaction techniques, so people are better able to use XRV to support everyday work tasks and recreational activities (Wang et al. 2022b). We have identified five key challenges that require ongoing investigations before XRV in the metaverse can be a reality:

1) Research into X-ray intuitive and XRV interactions is still a young field and, requires much work to find a novel way to determine when someone wants to be able to see through a wall.
2) While X-ray visualisations have been researched extensively, there has been little work looking into other XRV effects.
3) Research to date has not yet been able to calibrate someone’s natural sight to the real world completely (Arefin et al. 2024; Clarke et al. 2022) which impacts XRV techniques.
4) A metaverse would rely heavily on collaboration but has not been explored regarding XRV.
5) Sensor data research has focused on radiology approaches or photographic sensors. It could focus on displaying radar or Wi-Fi data in a 3D view, enabling many more different XRV applications (Adib and Katabi 2013).

15.6 Conclusion

A true AR metaverse has yet to be built or tested (Asif and Hassan 2023), and as highlighted in this chapter, many issues concerning XRV need to be addressed. Technically, we seem to have a good grasp on how to make an XRV technique work on various devices. However, there is still a large gap in research looking at how a user will interact with this type of data, especially around a large area a metaverse would require. XRV has been used in some commercial products that could be applied to the metaverse. However, there are still a lot of unknowns as to how XRV can be used to collaborate with other people and what is and is not useful.

This is a preprint of the following chapter: Thomas J. Clarke, Ian Gwilt, Joanne Zucco, Wolfgang Mayer, and Ross T. Smith, Superpowers in the Metaverse: Augmented Reality Enabled X-Ray Vision in Immersive Environments, published in Augmented and Virtual Reality in the Metaverse Context: The Impact on the Future of Work, Education, and Social Interaction, edited by Vladimir Geroimenko, 2024, Springer Nature Switzerland reproduced with permission of Springer Nature Switzerland The final authenticated version is available online at: ***https://doi.org/10.1007/978-3-031-57746-8_15***

Acknowledgements The authors would like to acknowledge the Australian Government Research Training Program Scholarship for funding this research, Bradley Richards for Illustrating Fig. 15.1, and Ha Chau Nguyen for helping editing this chapter.

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