AI & SOCIETY
https://doi.org/10.1007/s00146-022-01420-3

ORIGINAL PAPER

Technological mediation and 3D visualizations in construction engineering practice

Hans Voordijk[1] · **Léon olde Scholtenhuis**[1]

Received: 18 August 2021 / Accepted: 18 February 2022

Abstract

The generation and use of 3D images and visualizations through remote sensing, Building Information Modeling, and Augmented Reality technologies, have come to play a significant role in construction engineering practice. Although these technologies are promising, their potential can be misjudged when potential end-users are unaware of key assumptions that were made by developers. Realistic expectations require insights into the ways in which these technologies transform input collected into 3D visualizations and how these visualizations are possibly used on construction sites. This study's objective is hence to explore the form of technological mediation that the generation and use of 3D images and visualizations provide between a human and objects, or aspects of these objects, that would otherwise be largely imperceptible to professionals in construction practice. We show that algorithms pre- and post-process data through their technological selectivities, which function as mediators. Double mediations of augmented and engaged relationships play a dominant role in the use of 3D images and visualizations and enhance the situational awareness of professionals in construction practice. This is the first study that applies this perspective to increase the understanding of the mediating role of 3D images and visualizations in construction practice.

Keywords Postphenomenology · 3D visualizations · Technological intentionality · Digital materials · 3D laser scanning · Ground penetrating radar

1 Introduction

The digitization of three-dimensional (3D) building data through remote-sensing technologies, Building Information Modeling, and Augmented Reality has come to play a significant role in construction engineering practice (Lu et al. 2015). Building Information Modeling (BIM) is a key digital technology that serves as a software platform representing a digital model in which generated 3D data and other information about a project can be stored (Garbett et al. 2021). BIM models can be filled with 3D data from remote-sensing technologies that monitor a building or parts of a building during its whole life-cycle (Davtalab et al. 2018).

Remote-sensing technologies being rapidly adopted by the construction sector include three-dimensional (3D) laser scanning and ground penetrating radar technologies. Laser scanning technology (LST) has the ability to develop a 3D geometry of building and infrastructure objects—such as a building—through point clouds obtained from laser scans (Omar and Nehdi 2016). Ground penetrating radar (GPR) is another inspection technique capable of detecting subsurface properties through electromagnetic waves (Benedetto et al. 2016). By generating digital 3D building data in construction projects (O'Keeffe and Bosche 2015), these technologies support construction practitioners by mapping existing site conditions and enhance project control by providing means to monitor progress. LST and GPR necessarily use algorithms to automatically process the collected input and shorten the modeling process necessary to generate 3D images. By generating images of building objects or aspects of these objects that would be largely imperceptible to the human eye, LST and GPR extend human optical measurement capabilities. Nevertheless, these technologies need to be carefully calibrated, and deliver data that still require

---

✉ Hans Voordijk
j.t.voordijk@utwente.nl

Léon olde Scholtenhuis
l.l.oldescholtenhuis@utwente.nl

[1] Civil Engineering and Management, University of Twente, Enschede, The Netherlands

filtering and interpretation to support the decision-maker. Practitioners face several challenges during its use, because the interpretation of images is not straightforward and depends on training and expertise (Benedetto and Pajewski 2015).

BIM as a digital platform is also the basis for the use of 3D visualization devices on construction sites (Garbett et al. 2021; Williams et al. 2015). BIM-based 3D visualizations are used on construction sites by technologies that 'augment', or overlay, the real world with BIM data that seem to co-exist with the real world. Augmented Reality (AR) technologies add digital elements or objects to the user's surroundings (Liberati 2018). These digital elements and objects are superimposed on the everyday world that serves as the background. The digital objects are part of the visualization represented by a mobile AR device (Li et al. 2018). Mobile AR devices are portable displays and include smartphones, tablets, and wearable Head-Mounted Displays (HMDs). These allow users to interact with data from both actual and virtual building objects and to monitor construction progress by comparing the as-planned and as-built status (Dunston and Shin 2009). Mobile AR devices rely solely on data uploaded into the system, which makes its visualization features only as 'good' as the information they are based on. AR devices may invoke a 'false sense of security' in people if they do not have a full understanding of the technological working principles, and consequently misinterpret the technique.

Misunderstandings about how 3D images and visualizations are generated may lead to poor decision-making. Providing insights into the ways in which remote-sensing technologies transform data input into a BIM and how BIM-based 3D images and visualizations are used on construction sites will contribute to more realistic expectations about what these technologies can do. Studying this transformation from data input to visible output is also the focus of the philosophy of technological mediation. (Fried 2020; Friis 2017; Ihde 2009; Rosenberger 2013; Verbeek 2015). The central idea of this philosophy is that technologies mediate the relationship between humans and the world they experience (Coeckelbergh 2020; Ihde 1990; Verbeek 2006). The objective of this study is to explore the form of technological mediation that the generation and use of 3D images and visualizations provide between a human and objects, or aspects of these objects, which would otherwise be largely imperceptible to professionals in construction practice. Two major questions are how are 3D images and visualizations generated, and how do they interact with their users? The scientific contribution of this study is in connecting the generation and use of 3D images and visualizations on construction sites to this technological mediation perspective. As a first study in the literature, we adopt concepts of 'responsive digital materials' and their 'technological intentionality' as lenses to study how 3D images and visualizations are generated in construction engineering practice. Their use in this practice is analyzed by adopting the lens of 'double mediation' of 'augmentation relationships' of Rosenberger and Verbeek (2015). In an augmentation relationship, a technology directs a user's intention in different directions.

In this study, we first elaborate on the concept of technological mediation: its philosophical background and Ihde's typology that describes different 'actant roles' or ways that technologies mediate one's perception of the world. We discuss the transformation of data inputs into outputs in terms of 'responsive digital materials' and their 'technological intentionality'. Second, the *generation* of 3D images and visualizations in construction practice is described through a review of the literature and empirical studies on LST and GPR using algorithms that process the collected input necessary to create these images. We also review empirical studies to explore the *use* of 3D images and visualizations augmenting the construction worker's view with representations and instructions to support on-site construction processes. Subsequently, we analyze the kind of technological mediation that the *generation* of digital 3D images and visualizations provides in construction practice through applying the concepts of responsive digital materials and technological intentionality. The *use* of digital 3D images and visualizations is analyzed in terms of different 'actant' roles and double mediation of augmentation relationships. Finally, conclusions are drawn.

2 Technological mediation

In this section, the background to the mediation approach is discussed first. Second, the use of data is discussed by elaborating on different 'actant' roles that technologies may play in shaping the thinking and acting of individuals. Third, we discuss the generation of 3D images by conceiving technologies and their inbuilt selectivities as responsive digital materials.

2.1 Background to the mediation approach

The underpinning philosophy of technological mediation is phenomenology. In phenomenology, intentionality is seen as the core concept in understanding relations between humans and the world (Verbeek 2008). Phenomenology re-evaluates the modernistic separation of subject and object, such that there is always an intentional relationship between subject and object. Every instance of experience has a direction toward what it is that is experienced. "Because of the intentional structure of human experience, human beings can never be understood in isolation from the reality in which they live" (Verbeek 2008) [p. 388]. There are inextricable connections between humans and the world. 3D images and visualizations in construction are part of this world and thus subject to the same object-subject relationships.

In the philosophy of technology, phenomenology has been used to describe how using technology shapes human experience (Rosenberger and Verbeek 2015). Postphenomenology adds to phenomenology the mediated character of this intentional relationship between subject and object: “there is no direct relation between subject and object, but only an ‘indirect’ one, and technologies often function as mediators” (Rosenberger and Verbeek 2015) [p. 12]. That is, humans do not perceive the world *directly*, but always *through* a mediating technology that helps shape a specific relationship between humans and the world (Verbeek 2008). In effect, the human–world relationship is a human–*technology*–world one (Rosenberger and Verbeek 2015). Postphenomenology emphasizes that humans and technologies are not separate entities and can only be understood in their interrelations with the world and humans.

This approach was inspired by the rise of science and technology studies (STS) in the 1980s and 1990s and relates to the actor network theory of Latour (1996) in studying hybrid characteristics of human–technology relationships. In STS, sociological approaches are used to explore the effect of organizational and institutional factors on the development of technologies and the influence of society on technological design (Bijker and Law 2000; Schweber and Harty 2010). In the actor network theory of Latour, both humans and ‘nonhumans’, i.e., technologies or physical objects, should be understood as actors. Latour refers to these elements as ‘actants’. This actor–network approach has also been applied in several construction contexts: e.g., innovation (Harty 2008), visualization practices (Ewenstein and Whyte 2009), and collaboration in industrialized housing (London and Pablo 2017). Technologies that function as ‘actants’ may force certain behaviors on humans by carrying a ‘script’ (Akrich 1992) that guides users in the same way as a script steers actors in a theater play. The mediation effect is that the technology may influence users or direct people in certain directions.

Postphenomenology and sociotechnical approaches essentially emphasize that technologies are not passive entities but actively co-shape what actors do (Verbeek 2005). The concept of technical mediation takes a middle position between the extremes of technology as a script dictating its own direction and determining society (technical determinism) and technologies as neutral instruments (instrumentalism).

2.2 Different actant roles of technology

A technology only acquires its function as actant in a specific use context, while this use context is at the same time shaped by a technology as actant. It is in the specific use context of construction sites that the different actant roles of digital 3D images and visualizations are studied.

Ihde (1990) and later Verbeek (2005) analyzed actant roles by distinguishing different forms of human–technology relationships. Table 1 shows the well-known typology of Ihde, describing how technologies mediate one’s perception of the world—through embodiment, hermeneutic, alterity, and background relationships. This categorization of forms of mediation distinguishes the roles that technologies may take in shaping the thinking and acting of individuals. It ranges from technology as a ‘quasi-me’, which sees technology as an extension of a human, to technology as ‘quasi-other’, which refers to technology with a certain independence from the individual (Munters 2017).

First, in an embodiment relationship, a humans perceive the world through technology, but their attention is not directed to the technology itself. Technology is an extension of the body (Verbeek 2015). Spectacles, for instance, mediate between the viewer and the world (Ihde 1990). After a certain period of adaptation, this technology becomes almost invisible to its users. Related to this is Heidegger’s tool analysis and the concept of ‘readiness-to-hand’. Here, one relates to a technology as ‘quasi-me’.

Second, the hermeneutic relationship also addresses experiences of the world through technology. However, in contrast to the embodiment relationship, this form directs one’s attention to the technology itself without users explicitly interacting with it. Technology represents a specific aspect of the world, and this representation needs to be interpreted—hence the name ‘hermeneutic’ (Turk 2001). The use of a particular technology causes a person to experience a certain aspect of reality, that which is amplified, while, simultaneously, the experiences of other aspects of reality are reduced.

Third, toward the other end of the spectrum, Ihde describes alterity relations. The technology itself forms the center of attention for an individual who wants to perform a task enabled by it (Verbeek 2015). Humans interact with technologies as if the technologies have more-or-less their own agency. Technology appears as a ‘quasi-other’ to a human, possessing a certain kind of independence. Human intentionality is directed toward the technology itself. Here, humans are not perceiving the world through a technology

Table 1 Ihde's human–technology–world relationships

Type of relationship	Schematic representation
Embodiment relationship	(Human-Technology) → World
Hermeneutic relationship	Human → (Technology-World)
Alterity relationship	Human → Technology (-World)
Background relationship	Human—(Technology/World)

(the embodiment relationship) or by means of technology (the hermeneutic relationship), but are focused on the technology itself (Ihde 2009; Verbeek 2005).

Fourth, technology can function in a background relationship, in a more marginal sense than in the other mediations, in that the technology is not deeply experienced (Verbeek 2015). In this relationship, technologies help to shape the context through which we experience the world but in a way that is often not consciously perceived. These technologies are not explicitly experienced themselves but, nevertheless, have an impact on our relationship with the world. The technology is not embodied, and the world is not perceived through it (Rosenberger and Verbeek 2015). Unlike in the alterity relationship, the focus is also not on the interaction between humans and technology. In general, in this relationship, humans do not give the technology their attention.

When technologies play different actant roles at the same time, other human–technology–world configurations may emerge. In such situations, Rosenberger and Verbeek (2015) speak of an ‘augmentation relationship’. In such a relationship, the human directedness at the world can be described as ‘bifurcated’. There is a split in people’s directedness at the world, because parallel fields of attention emerge. Rosenberger and Verbeek (2015) give the example of Google Glass. Their users both have an embodiment relation with the Glass itself, and a hermeneutic relation with its screen that offers a representation of the world (ibid. p. 22).

2.3 Built-in selectivities and responsive digital materials

The *generation* of 3D images and visualizations is discussed by conceiving technologies and their inbuilt selectivities as responsive digital materials. According to Verbeek (2008), “hermeneutic relations always involve a technologically generated representation of the world”. This is the result of a “specific technological directedness at the world: thermometers focus on temperature … sonograms on how material objects reflect ultrasound” (Verbeek 2008) [p. 393]. This directedness of “the sensing apparatus” of a technology is configured to process inputs in certain ways (Ihde 1990; Wiltse 2014). Ihde explains this technological directedness at the world as “instrumental intentionalities or built-in selectivities in technologies” (Ihde 2015) [p. xv]. Technological intentionality is the specific way in which a technology is directed at a specific aspect of the world. Not all technological intentionalities are directed toward representing an aspect of the visible world: some construct a reality of aspects of the world that are unobservable by humans. Verbeek (2008) offers the example of radio telescopes that produce a visible image of a star based on radar waves that are invisible to the human eye. Similarly, remote-sensing technologies have the ability to “transform otherwise imperceptible objects of study into a form possible for human bodies to perceive” (Rosenberger 2013) [p. 76].

Furthermore, remote-sensing technologies can be conceived as ‘responsive digital materials’. ‘Materials’ or the concept of ‘materiality’ addresses the entanglement of the physicality of technologies and human activities and relationships (Orlikowski and Scott 2008). Also, digital technologies have a certain materiality (Poulsgaard and Malafouris 2020; Wellner 2020). Responsive digital materials consist of physical devices and digital codes. Mediation through digital materials is based on a ‘substrate’ that responds to an ‘activity’ in such a way that the substrate is inscribed with a ‘trace’ of that activity (Wiltse 2014). The substrate is the medium that enables the transmission of the trace content (Wellner 2018). Traces are resulting perceptible changes in these substrates. The relationship between substrates and traces determines how the ‘input’ received is made visible as ‘output’**.** Traces of registered activities are made visible in the digital material itself.

Digital material mediation can be conceptualized as human → ([trace | substrate] → world) (Wiltse 2014). A remote-sensing technology, as digital material, can be represented as [trace | substrate], with the substrate facing the physical world and the trace facing the perceiving person (Wiltse 2014). With remote-sensing technologies that produce an image, the technology as substrate responds to a phenomenon in the physical world and is the interface between objects in the physical world and its captured digital representation. In creating a visual image, this technology as a digital material responds to activities in line with how it has been designed and programmed its technological intentionality. Algorithms are designed to automatically process the collected input and shorten the modeling process necessary to create understandable images. In this way, algorithms function as mediators between users of visible images created and objects that are not visible to the human eye (see also Wellner 2020). Users of GPR and LST interpret these images of traces made visible by algorithms to gather information about the project site.

It is shown that technologies may play different ‘actant’ roles by influencing or directing users in certain directions. The well-known typology of Ihde distinguishes the roles that technologies may take in shaping the thinking and acting of individuals. A technology-generated representation that is interpreted by a human is the result of built-in selectivities in technologies directed at a specific aspect of the world. In generating such a representation, a technology as digital material responds to the input in line with how it has been designed and programmed. We adopt concepts of built-in selectivities and responsive digital materials as a lens through which to analyze how 3D images and visualizations that shape the construction professional’s understanding of the world are *generated*. Using Ihde’s typology, it is analyzed how 3D images and visualizations may play different ‘actant’ roles at the same time when *used* on construction sites.

3 Research design

In the introduction section, it is explained why this study is undertaken, followed by introducing the basic theoretical concepts in the subsequent section. In this section, the two following steps of this research are introduced: (1) a review describing GPR and LSR prototypes and empirical studies on the generation and use of 3D images and visualizations on construction sites; (2) a discussion on the kind of technological mediation that both technologies provide in construction practice through applying the concepts of technological selectivities, digital materials, and double mediation. Table 2 shows the research design.

First, we review studies that elaborate on the way the acquisition and processing of data and data modeling take place using GPR and LST. That is, how GPR and LST receive ‘input’ and transform this into visible ‘output’. Both LST and GPR are detection techniques that ‘translate’ the input they collect into 3D images that humans are able to perceive and understand. These images mediate one’s experience of the world—of an otherwise invisible object or invisible aspects of an object (Friis 2015). With its emphasis on human practices and experiences, postphenomenology views empirical studies (work of others or self-conducted studies) as the basis for philosophical reflection (Rosenberger and Verbeek 2015).

The exploration, of generating 3D images through GPR in construction practice, was drawn from an ongoing empirical program carried out at the authors’ research institute. Part of this program was the review of empirical studies on developing methods that could identify subsurface infrastructure. Exploring the generation of 3D images by LST in construction practice was part of another research project, also carried out at the authors’ research institute. Part of this research project was the review of empirical studies on developing and implementing algorithms that could process point cloud data, collected through internal and external scanning of a building, into 3D coordinates. The focus was on imperceptible geometric details of the visible surface of a building. Empirical studies on the use of 3D images and visualizations of the existing buildings and on-site subsurface infrastructure were also reviewed. Mobile AR devices can orient and display 3D virtual models over a camera image by adding 3D information to visual models. In the empirical studies reviewed, the focus is also on mobile AR devices that augment a construction worker’s view by adding assembly instructions, such as Head-Mounted Displays (HMDs). 3D

Table 2 Overview of the research design

	Conceptual background	Review of empirical studies	Analysis of technologies reviewed	Discussion
Generation of 3D images and visualizations	Built-in selectivity digital responsive materials	LST and GPR: algorithms processing data collected through scanning	LST and GPR: digital responsive materials with built-in selectivities	Built-in selectivity and double mediation related to epistemic uncertainties, adoption, and human blindness
Use of 3D images and visualizations	Actant roles augmentation relationship	Mobile AR devices: augmenting a construction worker’s view	Mobile AR devices: double mediations through parallel relationships of mediation	

images and visualizations can be integrated in an HMD to enhance the user's view on the site.

Second, conceiving LST and GPR technologies as responsive digital materials initiates a postphenomenological analysis on how technological intentionality makes certain aspects of reality accessible to humans through data processing. The focus is on "the specific way in which a specific technology can be directed at a specific aspect of reality" (Verbeek 2008) [p. 393]. This directedness is programmed into the technology by its developers. The directedness of the sensing apparatus of each of the technologies reviewed, or their built-in selectivities (Ihde 2015) [p. xv], is elaborated with descriptions of how the sensing apparatus is configured to acquire input in certain ways (Ihde 1990; Wiltse 2014). Both LST and GPR receive 'input' and transform this into visible 'output'. Using the concepts of built-in selectivities and responsive digital materials, we analyze how through data processing, LST and GPR *generate* images that will cause a user to experience a certain, amplified, aspect of reality, while the experience of other aspects of reality is simultaneously reduced (Ihde 1990).

The *use* of 3D visualizations on construction sites is analyzed by applying the concept of double mediation of augmentation relationships. We elaborate on this by analyzing how mobile AR devices have the ability to direct a user's intention in different directions (i.e., the mediation effect of technology). The taxonomy in Table 1 served as a framework to identify the phenomenological relationships analyzed. By understanding the different mediating or 'actant' roles of mobile AR devices, in an augmentation relationship, we provide insights into what these technologies actually do in construction practice.

4 Review of empirical studies

Technologies such as GPR and LST and Building Information Modeling (BIM) significantly overlap, since GPR and LST are about the generation of 3D visualizations and BIM is often about their use on construction sites. The generation of 3D images and visualizations through GPR and LST is described first. Second, their use on construction sites is described.

4.1 Studies that generate 3D visualizations with GPR

A common problem in utility construction is the uncertainty over the whereabouts of the subsurface infrastructure. Practice typically relies on 2D printed maps, which poses the risk of being misinterpreted through human error. These maps are hard to interpret, since they do not provide insight into the 3D spatial layout of the crossing subsurface infrastructure lines. Therefore, the civil engineering domain commonly uses GPR to locate and map subsurface objects such as pipes, cables, and other utility network components (Benedetto and Pajewski 2015). The core components of a GPR system are a transmitting unit, a receiving unit, a data control unit, and a data display unit. The transmitter antenna within a GPS system transmits high-frequency electromagnetic waves into the subsurface and uses a receiving antenna to record reflected signals (Jaw and Hashim 2013). The recorded two-way time, i.e., the time a wave takes to travel from the transmitted antenna to an object and back to the receiving antenna, allows the operator to detect where the structure below the ground level has various electromagnetic properties (Metje et al. 2007). This is because, when the transmitted radar wave travels through the subsurface and encounters materials with different electrical properties (referred to as permittivity and conductivity), it reflects waves differently (Bostanudin 2013). Hard cylindrical shapes, such as cables and pipes, for example, may become visible on radargrams as hyperbolas. A problem is that the moisture content of the ground also influences radar waves. Ground water is conductive and hence reduces the reflection of emitted signals back to the receiving antenna.

How radargrams represent cables depends on whether surveyors undertake ground scans using longitudinal (alongside a pipe), perpendicular (crossing a pipe at 90 degrees), or angle-variation scanning approaches (Jaw and Hashim 2013). Since the amplitudes of the radar-reflected signals provide information about subsurface properties, producing a good data display is an integral part of, and key to, GPR data interpretation (Bostanudin 2013). However, the signals reflected by the target are often weak and overlap with clutter and noise signals. A key objective in GPR data processing is therefore to improve the image quality of the obtained data and enable easier understanding and classification of subsurface objects. It is very difficult to comprehend a signal without some processing. For example, Jaw and Hashim (2013) use three types of pre-processing to avoid inaccuracies in radargrams: filter noise from non-targets, enhance visual quality of the radargram, and smooth the structures on the radargram (i.e., utilize gain control).

Post-processing of radar data can involve various steps to obtain useful information (Evans 2010). Post-processing of the data is necessary for creating a 2D utility plan or 3D model. Processing algorithms can correct for biases in data due to low frequencies and DC errors (subtract means); adjust the radar signal to correct for antenna reflections from the ground surface (time-zero corrections); adjust the relative amplitudes of weak, deeper wave signals (gain control); and remove human-induced noise (Li et al. 2015). In other words, background noise and clutter effects, as well as unwanted signals, are removed or suppressed (Bostanudin 2013). Processing is often carried out iteratively with data flowing around the processing loop several times. Such steps eventually improve the signal-to-noise (STN) ratio and enhance the data display (Jol 2009).

Despite the improved detectability of pipes after this processing, GPR scans inherently remain open to outputs that contain location errors in both position and depth. For example, the standard deviation of errors increases with buried depth (Li et al. 2015). To cope with this, one can integrate GPR with geographical data (e.g., GPS) in visualization systems to show end-users the positional uncertainty of GPR scans. Here, three-dimensional probabilistic bands are generated that can be applied to a scanned utility line location (Li et al. 2015; olde Scholtenhuis et al. 2018). Highly skilled human operators are required to apply such filters to measured data and to make sense of the captured images (Bostanudin 2013) [p. 195].

The raw data collected with a GPR are sufficient to give a good indication of the presence of cables and pipes. Therefore, if the purpose of a survey is only to *detect* existing underground infrastructure, then pre-processing of the collected data is sufficient. Then, to avoid damage, it is sufficient to indicate the rough location of cables and pipes by placing markers on the surface.

4.2 Studies that create 3D visualizations with LST

The digitization of 3D building data has been a rapidly developing approach to 'as-built' information management. An as-built building information modeling process has two major stages: data acquisition and processing, and data modeling (Jeong et al. 2004; Pătrăucean et al. 2015). The introduction of LST represented a major change in terms of data acquisition. LST is capable of recording the location of a large number of points in space (Walsh et al. 2013). It has the ability to capture the 3D geometry of an asset in the form of point clouds through collecting millions of 3D data points accurate to within millimeters. A laser scan sends a laser pulse to an object and measures, based on travel time, the distance between the transmitter and a reflecting surface (Boehler and Marbs 2002). This reflecting surface could, for example, be a building façade. These laser scanning measurements result in several data files that together represent the distinctive views of a building façade. Specifically, these files store X, Y, Z values as text for each surveyed 3D data point.

To convert the data collected through LST into useful information, it is necessary to process these data points (Walsh et al. 2013). This processing begins with extracting information about each individual point and then employing relationships between points to derive properties of the underlying surface and object. The aim is to detect building elements, or features of these elements, within the scanned environment. Building elements can be identified from scans through filtering and processing algorithms applied to the 3D point clouds. This generally involves geometric modeling of the point cloud data, recognizing geometric objects from point cloud data, and finally establishing semantic relationships between them to result in an as-is Building Information Model (BIM) (Gao et al. 2012; Xuesong et al. 2012).

The 'point cloud modelling' process is generally composed of three steps: (a) identifying the building elements to be modeled from the point cloud data; (b) tracing the points to determine the location and the dimension of the building elements; and (c) extracting building models from scan data using modeling. Automating these tasks through mathematical algorithms speeds up the modeling process. These algorithms may address the following tasks (Pătrăucean et al. 2015):

1. Point cloud clustering: given predefined criteria, clustering the input points to provide *segments of points*.
2. Geometric detection and triangulation: reporting if and where simple *predefined geometric shapes* appear in a segment of a point cloud.
3. Shape *fitting*: given a subset of the original point cloud and a predefined 3D model, determining the geometric parameters of a component in the model.
4. *Classification*: given the segmented point cloud obtained above, assigning a unique building element label or semantic property to each segment.

The point cloud for detecting the stories of a building is a text file containing the recorded X, Y, Z values of each point. The program reads the file, line by line, assigns coordinates to points, and records them in a matrix. Initially, the point cloud lacks any structure. The priority is labeling its points and allocating them to building stories. This is carried out based on two premises. First, the points representing each floor or ceiling will have almost the same height (Z) value. As such, a scan will contain a large number of points with similar Z values around each floor and ceiling. Second, lasers can only scan spaces visible to the eye. In other words, areas that are not occluded. Consequently, points cannot be collected in invisible areas, so the volume between the ceiling of one story and the floor of the story above are expected to be free of scan data. The data points identified can, in turn, be imported into commercial modeling tools. As such, point clouds, after translating the points into 3D triangular mesh shapes, surfaces, and solids, can generate 'as-is BIMs'.

4.3 Use of 3D visualizations

BIM-based data and visualizations on construction sites are used by mobile AR devices that 'augment', or overlay, the real world with BIM data that seems to co-exist with the real world. Main uses of mobile AR devices that overlay

BIM data onto the construction site are to visualize what is not yet built (i.e., the future) and to view what is hidden (e.g., buried elements, or elements obstructed from view) (Abboud 2014).

The uses of these 3D visualization devices first visualize what is not yet built. These devices have merit in communicating and showing design ideas, and therefore, design issues can be more adequately discussed (Hartmann et al. 2008). With 3D visualization devices, it is better visible what the design actually involves and less time is needed for explaining. It is possible to quickly load alternative designs in the 3D visualization device and compare the advantages and disadvantages of alternatives, i.e., the different impacts on the surroundings. A 3D visualization enables people to 'walk through' the designed building object and to experience the impact of the construction on the project location. It provides actors the ability to interact with objects within virtual 3D environments. Projects that are visualized in 3D add greater realism. Consequently, they reduce the likelihood of misunderstanding the design compared with 2D drawings.

These 3D image and visualization devices can also be interfaced with a real-world construction site, allowing users to compare the as-designed model with the as-built condition or as-built model. Differences between as-built and as-designed BIM models are very common in construction projects as the details of a constructed object often deviate from the design due to changes of the building during its lifetime and constructability errors. 3D visualizations can reduce clashes between existing and new building objects through the application of 3D clash detection (Akponeware and Adamu 2017). Without 3D visualizations, clashes are mostly only found during construction. 3D visualizations increase engineers' understanding of the complexity of the underground networks by showing actual sizes of the utility infrastructure and the positions and relationships between buried utilities.

On construction sites, 3D visualizations devices allow users during construction to interact with both actual and virtual objects, monitor construction progress by comparing the as-planned and as-built status of (part of) a project (Dunston and Shin 2009), and support decision-making processes onsite (Xi et al. 2018). These visualization devices enable engineers to obtain awareness about details of the assembly and construction of works.

Devices, such as HMDs, can display instructions to those assembling components using either voice commands or visual display cues. Instructions through 3D visualizations allow workers to concentrate on the assembly task without the need to interpret written manuals (Davies and Harty 2013). Large-scale construction sites benefit from mobile AR-aided site navigation, particularly where key building elements, such as stairs, have yet to be constructed. On large-scale, complex sites, users may find it difficult to position themselves on the site using plans of the proposed final building, and way-finding visualization devices may prove more useful in guiding workers to their desired destination.

Major advantages of an HMD over a paper-based communication are the parallelization of information gathering and a reduction in time spent searching for information when the data are already displayed in the user's field of view. Compared to the paper-based alternative, the provisions of instructions in the HMD reduce the likelihood of making substantial mistakes and remind users of instructions that they might otherwise have overlooked. The main reason for this is the ability of the HMD to provide context-aware instructions using clear and unambiguous visualizations (Shatte et al. 2014). People prefer receiving instructions through a series of sequential information visualizations rather than in one instruction (such as a construction drawing) including all the information required**.**

In addition, the speed of assembly increases significantly using the HMD, because the users do not have to manually filter instructions from the information carrier to deduce the correct actions. Instead, they receive augmented instructions directing them to the assembly location. Most of the users find these received directions to the required locations, and the instructions on where to bring and assemble specific elements, convenient. This reduces their cognitive load (Dunston and Shin 2009) and gives them a feeling of comfort, as they trust the instructions on the HMD to be correct.

5 Analysis

We first analyze the generation of 3D images and visualizations through GPR and LST by conceiving remote-sensing technologies and their inbuilt selectivities as responsive digital materials with substrates and traces. Second, the use of resulting 3D BIM images and visualizations establishing various mediation relationships and playing different actant roles is analyzed. It is argued that there are double mediation relationships when using 3D BIM images on construction sites. In other words, using 3D BIM images is not exclusively bound to one type of mediated relation.

5.1 Responsive digital materials and generating 3D images

The GPR system, as a 'substrate', transmits a radar wave into the ground and records the time taken for this pulse to be reflected. The trace is the recorded output of the received GPR signal (Bostanudin 2013). This trace is converted into a radargram consisting of a sequence of monochrome shades as hyperbolas showing the amplitude of the GPR trace [ibid.]. Data editing and filtering are used to improve GPR image quality and enable easier detection of objects in the subsurface infrastructure. In creating a utility map, ‘reduction’ and ‘amplification’ take place in ‘removing’ and ‘suppressing’ background noise, clutter effects, and unwanted signals, in correcting for low-frequency bias and topography effects in the data, and in improving the signal-to-noise ratio and data display (Jol 2009).

A 3D utility map is the result of inbuilt selectivities of a GPR (Ihde 2015) of data pre- and post-processing algorithms (Fig. 1). Pre-processing algorithms focus on avoiding inaccuracies, filtering noise from non-targets, and enhancing the visual quality of the radargram (Jaw and Hashim 2013). Post-processing algorithms can correct for biases in data due to low frequencies and errors, adjust the radar signal for antenna reflections from the ground surface, alter relative amplitudes of weak deep-wave signals, and remove human-induced noise (Li et al. 2015). Here, background noise and clutter effects, as well as unwanted signals, are removed or suppressed (Bostanudin 2013).

In LST, the laser scan serves as the *substrate* that sends a laser pulse to an object to measure the distance between the transmitter and the reflecting surface (Boehler and Marbs 2002). The resulting *traces* are in the form of point clouds of millions of 3D data points accurate to within millimeters (Walsh et al. 2013). Based on these *traces*, the 3D geometry of a building can be captured through ‘reduction’ and ‘amplification’: by extracting information about each individual point and then employing the relationships between points to derive properties of the underlying surface and object. This is translated into a 3D image of building elements, or features of these elements, within the scanned environment.

This 3D image is based on the inbuilt selectivities of LSTs (Ihde 2015) (Fig. 2). These selectivities are mathematical algorithms that speed up the modeling process using predefined criteria. Data points are clustered to obtain segments of points and to report if and where predefined simple geometric shapes exist. Fitting a predefined 3D model to each segment results in a unique building element being assigned. To create a BIM from point cloud scans, an algorithm is used to segment the point cloud into floor points, ceiling points, and other points. The inbuilt selectivity of this algorithm assumes building stories to be composed of horizontal floors and ceilings plus vertical walls and openings (doors and windows). The algorithm detects these horizontal and vertical surfaces, and labels their related points. To remove the irrelevant points for the subsequent identification of walls, openings, ceilings, and floors the algorithms perform data ‘reduction’.

5.2 Double mediation and use of 3D visualizations

This study shows that 3D images and visualizations may play different ‘actant’ roles (Latour 1992) in construction. People using mobile AR devices on site receive various types of information, including 3D images and text about the objects and buildings they see in their environment. A mobile AR device virtually superimposes representations of buildings or subsurface infrastructure over the real environment. This hermeneutic relationship between users of the mobile AR technology and the information that it provides about the project is complemented by an embodiment relation. Users may perceive or experience the project and its environment through a mobile AR application. If AR devices become integrated in routine behavior, they might even be experienced as natural extensions of the body (Riemer and Johnston 2014). Once users have gained the skills and expertise necessary to work with them automatically, in an unreflective way, the AR devices become equivalent to the ‘ready-to-hand hammer’ of Heidegger (Dias 2006; Dreyfus and Dreyfus1996). When mobile AR devices achieve a

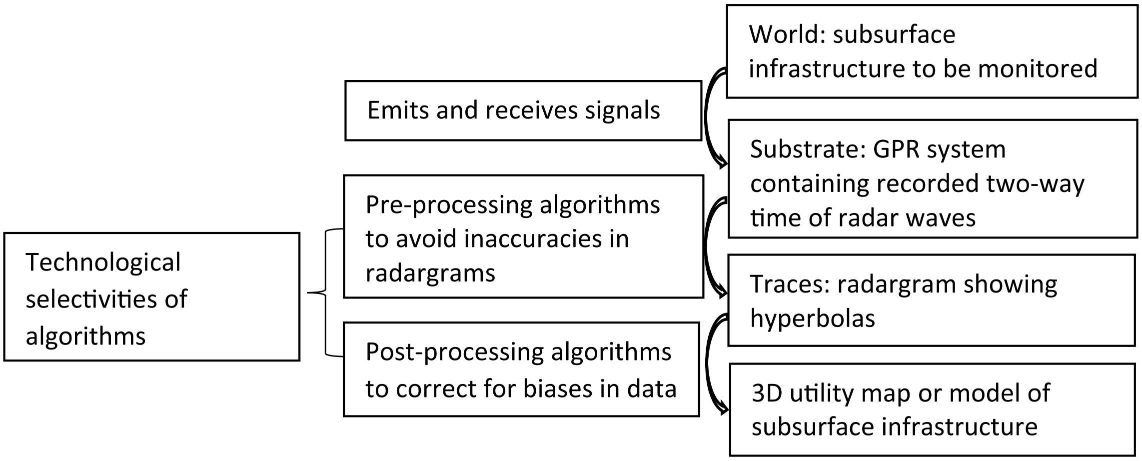

Fig. 1 Technological mediation and ground penetrating radar

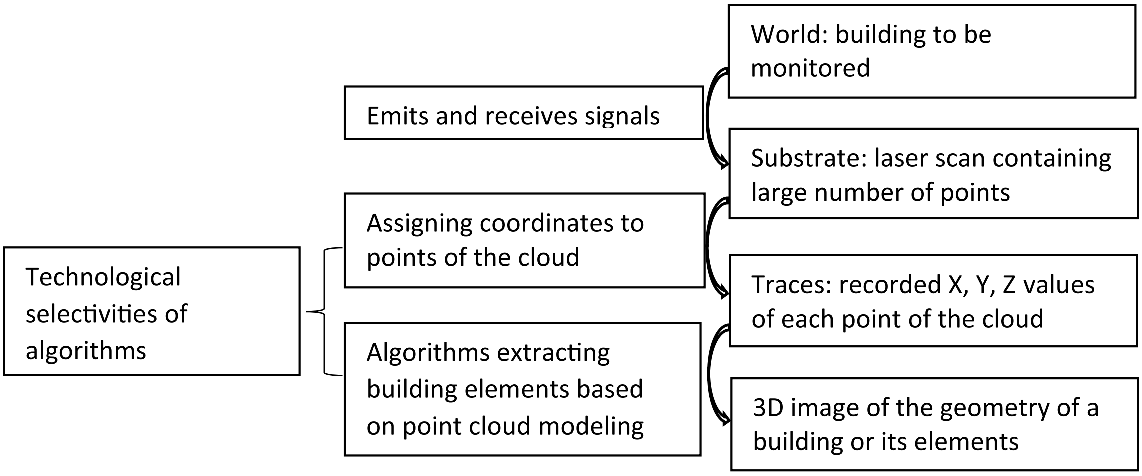

Fig. 2 Technological mediation and laser scan technology

'natural' incorporation in daily routines, one can speak of an embodiment relationship to the project environment.

As such, mobile AR involves a double mediation: there is a 'quasi-me' embodied relationship when perceiving the project environment through AR technology, and a hermeneutic relationship with the screen that offers representations of the project (Rosenberger and Verbeek 2015). As such, a mobile AR device in construction practice offers not one, but two parallel relationships with the world. Schematically, this can be represented as follows:

$$\begin{aligned}&(\text{Human} - \text{Technology}) \rightarrow \text{World}\\ &\qquad\qquad\qquad \searrow (\text{Technology} - \text{World}).\end{aligned}$$

In such situations, Rosenberger and Verbeek (2015) speak of an augmentation relation. The human directedness at the world around them in such layered 'augmentation relationships' can be described as 'bifurcated'. There is a split in people's directedness at the world, because two parallel fields of attention emerge. First, mobile AR serves as a second layer of 'augmentation' that is added to the physically interpreted project environment, i.e., "a field of attention to be intentionally directed to" alongside the physical reality (Rosenberger and Verbeek 2015). Second, users are directed to the project site and project information displayed through the mobile AR technology.

Mobile AR can also direct users to the instructions that appear on the screen, rather than to the environment itself. Users consequently focus more on these augmented instructions than on the projected 3D image of the physical project environment. In this type of relationship, the mobile AR device functions as a 'quasi-other' to which users relate by following its intelligent instructions (Hogan and Hornecker 2011). This device is experienced as having its own agency with which users interact. In terms of Latour (1992), this device encourages certain behavior by carrying a 'script' that guides workers in a certain direction.

By directing human attention to the virtual instructions, a new parallel relationship of augmentation can be identified, namely one in which the mobile AR device is perceived as a technology with which one must interrelate, i.e., an alterity relationship. Here, AR involves another double mediation: while users are directed to and perceive the world through AR (an embodiment relationship), they are also directed to the virtual instructions that are visualized (an alterity relationship). Schematically, this double mediation relationship can be visualized as

$$\begin{aligned}&(\text{Human} - \text{Technology}) \rightarrow \text{World}\\ &\qquad\qquad\qquad \searrow \text{Technology} (- \text{World}).\end{aligned}$$

Augmentation through virtual instructions can create an 'intelligent' project context that is explicitly used to influence human actions and to produce particular outcomes within a construction project. In terms of Ihde (1990), an AR device, through virtual instructions in an alterity relationship, interacts with its users and mediates certain actions on a construction project through invitation and inhibition. The user receives information on how to process a certain object on site, and thus acts upon it. Furthermore, AR increases the ability to shape users' engagement with a project by introducing virtual instructions (Liberati 2016). As such, one can speak of an engaged relationship of augmentation.

In the context of a construction site, a mobile AR device forms an alterity relation through virtual instructions. These virtual instructions provided concern physical objects external to the augmentation. Therefore, after absorbing the instructions through the AR device, the attention of the users is directed to the physical non-augmented objects, the building elements on site. In other words, when mobile AR is directing human attention to the virtual instructions in an alterity relationship, the user's relation with the construction project environment is, in Ihde's terminology, initially a background one. When human attention is subsequently directed to the building elements, the virtual instructions through MAR move into the background of one's perceptions. Through the virtual instructions, the users' become engaged with the construction project: they begin to change the existing project conditions.

6 Discussion

By generating 3D images and visualizations of building objects, or aspects of these objects, sensing technologies like GPR and LST extend human optical measurement capabilities. Nevertheless, users still face several challenges when interpreting these 3D visualizations because of the inbuilt selectivities of GPR and LST. A GPR—after inadequate processing, poor data collection, or due to the technological limitations—may be showing a 'clean' underground radargram without any hyperbolic signals signifying the existence of buried objects. This could lead to false-negative conclusions from a user that a scanned location is free of any utilities, while in fact, there might be a pipe cable on site. Further limitations are that a GPR generates images based on reflected signals, which makes it hard to 'measure' the exact geometry (Jaw and Hashim, 2013) of a utility line. Due to non-homogeneous properties of soil and the many possible underground network layouts, it is also challenging to identify multiple, co-located cables that lay closely alongside one another in the subsurface from radargrams.

Similarly, when applying LST, data collection may contain errors due to a surface's shape, color, and conditions of the object scanned (Anil et al. 2013). Occlusions and cluttered images may also 'hide' relevant information from the modeler, and eventually feed incomplete information to the decision-maker. Incomplete data collection through LST, because certain locations on the construction site are inaccessible for scanning, may hence result in modeling errors and wrong interpretations of the images provided.

The algorithms that pre- and post-process collected input from techniques such as GPR and LST function as mediators through their technological selectivities. These selectivities determine possible differences between generated 3D visualizations and the 'real' properties of the physical objects that are not visible to the human eye. These differences attribute to the so-called epistemic uncertainties. Epistemic uncertainty derives from the lack of knowledge of a phenomenon, process, or system (Basu 2017). In the case of GPR and LST, it occurs either from transforming inputs into outputs inside these technologies or from external factors generating 3D visualizations. Verbeek (2008) claims that inbuilt selectivities are not necessarily directed at accurately representing the world but, rather, constructs a certain way of seeing the world. In providing 3D images of objects, GPR and LST technologies, as digital material, respond to the input in line with how they have been designed and programmed.

Next to processing and selectivities, human intentionality comes into play when users 'read' and interpret the 3D images provided (Rosenberger and Verbeek 2015). These 3D images amplify a person's experience of a certain aspect of reality, while simultaneously reduce experiences of other aspects of reality (Ihde 1990). Reduction occurs, because the representation in a 3D BIM model or image is 'reduced' to views that can be expressed using the three-dimensional objects and properties available (Turk 2001). Through this reduction and amplification when using GPR and LST, a "blindness" may be created for other aspects of reality. Users limit their view to that, which can be represented in the 3D image or visualization as a result from technological selectivities as programmed and designed. As a result, users may interpret 3D images and visualizations in ways that match modeled reality and possibly disregard information that does not match this reality. When this results in 3D models that miss information about locations of utility lines, or geometric shapes of scanners facilities, this could result in incorrect interpretations of the images provided, and eventually lead to design errors and rework during construction.

Construction professionals frequently are not conscious of selectivities and intentionalities, and consequently consider the tool either as useful under all possible conditions, or not suitable at all. Failing to observe the conditions under which technologies mediate input into output, and the possibilities and limitations that processing algorithms provide, has eventually an impact on the end-user assessment of a technology. Ignoring this mediating role of the LST and GPR technologies in construction practice may result in faulty expectations about what these technologies can do. We thus argue for a need to be critical in assessing the output provided by these technologies. We posit that, when potential adopters acknowledge the mediating role of a technology, they can develop an appropriate set of decision criteria and applications contexts in which a technology needs to function.

It is shown that 3D images and visualizations may play different 'actant' roles (Latour 1992) at the same time. In the double-mediated augmentation and engaged relationships analyzed, one can speak of a dynamic back-and-forth movement between the hermeneutic and alterity relations on the one side and the background relation on the other. When the focus is on the virtual representations or instructions provided, human intentionality is directed to the technology and users' relation with the project environment is in the background. Conversely, when the user's attention is directed to the physical objects external to the augmentation, the virtual representations or instructions move to the background of one's perceptions.

Through this augmented double mediation, 3D images and visualizations through mobile AR will generally reduce the susceptibility to mistakes in interpreting plans or designs. More specifically, it reduces the user's 'cognitive load' by rendering a selected portion of a 3D model spatially on the user's view (Dunston and Shin 2009). Double mediation through a mobile AR device influences the 'risk awareness' of engineers and contractors. It allows practitioners to answer questions such as 'where can we dig safely?' and 'where do we need to execute work with extra care given the uncertainty boundaries and located existing infrastructures?'.

In sum, on one hand, technological intentionality through inbuilt selectivities may attribute to the so-called epistemic uncertainties. As a result from these selectivities, human "blindness" may be created, because users limit their view to that, which can be represented in the 3D image or visualization and disregard information that does not match this representation. On the other hand, the dynamic back-and-forth movement between the different relations through AR-enabled double mediations may lower the level of epistemic uncertainties. Compared to the typically employed printed maps or paper instructions, AR-enabled double mediation enhances context and situational awareness, and may reduce possible differences between interpretations of virtual representations and properties of physical objects observed.

7 Conclusions

This study's objective was to explore the form of technological mediation that the generation and use of 3D images and visualizations provide between a user and objects, or aspects of these objects, which would otherwise be largely imperceptible to professionals in construction practice.

Generating digital 3D images and visualizations in construction practice was described through studying data acquisition, processing, and modeling using GPR and LST in construction practice. It was described how GPR and LST receive 'input' and transform this into visible 'output'. We analyzed GPR and LST in terms of responsive digital materials and inbuilt selectivities. As such, both technologies are a 'substrate': the interface between objects in the physical world and their captured digital representation. A user of GPR or LST interprets images or 'traces' made visible by the technology itself. We conceptualized the digital material mediation of GPR and LST as human → ([trace | substrate] → world). We explained how the properties of physical objects could only be revealed by making the technological intentionality of GPR and LST accessible to human intentionality through 'reduction' and 'amplification' of the data collected.

We also explored the use of 3D images and visualizations augmenting the construction worker's view with representations and instructions. Using the four human–technology–world relations introduced by Ihde (1990), it was found that mobile AR devices can, depending on use practices or the context of use, establish a range of mediation relationships between the project environment or construction site and those who experience it. 'Non-interactive' mobile AR fits with Verbeek and Rosenberger's augmentation relation, and includes both embodiment and hermeneutic relationships as one not only perceives the construction site through a mobile AR device but also interprets the digital representation of the site revealed by such a device. The 'interactive' relation of engagement includes, in addition to an embodiment relation with the mobile AR device itself, also an alterity relation where interaction takes place with its users through virtual instructions. From this, we concluded that Verbeek's concept of double mediations may create more realistic insights into, and realistic expectations of, what technologies actually do. On one hand, inbuilt selectivities may attribute to the so-called epistemic uncertainties and human "blindness". On the other hand, the dynamic back-and-forth movement between the different relations through AR-enabled double mediations may lower these uncertainties. It is essential that the end-user understands this relationship to successfully align the features of a technology to support their project's goals.

These reflections contribute to the construction and engineering practice by showing that generating 3D images and visualizations through technological prototypes, systems, and algorithms involve intentionality from both the technology (or its developer) and its user. Understanding this complex interplay may eventually help in developing and tailoring better technologies, and may increase our understanding of how and why technologies are either adopted successfully or not. Neglecting this mediating role could result in misinterpretations or overly optimistic expectations about what these technologies can do.

The augmentation relation indicates that users treat the technology as a 'quasi-me', but that it is essential that users know the constraints and limitations of projected project representations. An engaged relationship shows that augmentation, through virtual instructions, may create an 'intelligent' project environment that is explicitly used to influence human actions and to produce particular project outcomes. These conclusions shape various questions for the design and uptake of mobile AR in construction practice. Fundamental questions include what information should be presented, how, and what should algorithms do with project elements that are not shown but are necessary for decisions to be made? We therefore encourage a closer analysis of technology–human interaction through additional field studies, replacing a technology-push approach with a more iterative development and adoption cycles with reflection on the technologies' mediated character. The framework we employed is promising for future studies in this area as it enables a deeper analysis of how new digital technologies that are entering the construction arena, such as IoT and cyber-physical systems, may steer user's assessments, decision-making, experiences, and expectations.

Acknowledgements We would like to thank the researchers of our ongoing empirical research programs for sharing their results.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors reported no potential competing interest.

References

Abboud R (2014) Architecture in an age of augmented reality. NAWIC, Fort Worth

Akponeware AO, Adamu ZA (2017) Clash detection or clash avoidance? An investigation into coordination problems in 3D BIM. Buildings 7(3):1–28. https://doi.org/10.3390/buildings7030075

Akrich M (1992) The de-scription of technical objects. In: Bijker WE, Law J (eds) (2000) Shaping technology/building society: studies in sociotechnical change. MIT Press, Cambridge, pp 205–224

Anil EB, Tang P, Akinci B, Huber D (2013) Deviation analysis method for the assessment of the quality of the as-is Building Information Models generated from point cloud data. Autom Constr 35:507–516. https://doi.org/10.1016/j.autcon.2013.06.003

Basu S (2017) Plant hazard analysis and safety instrumentation systems. Elsevier, London

Benedetto A, Tosti F, Ciampoli LB, Pajewski L, Pirrone D, Umiliaco A, Brancadoro MG (2016) A simulation-based approach for railway applications using GPR. In: 16th International Conference on Ground Penetrating Radar (GPR)

Benedetto A, Pajewski L (2015) Civil engineering applications of ground penetrating radar. Springer, Cham

Bijker W, Law J (2000) Shaping technology/building society: studies in sociotechnical change. MIT Press, Cambridge

Boehler W, Marbs A (2002) 3D scanning instruments. Proc CIPA WG 6:9–12

Bostanudin N (2013) Computational methods for processing ground penetrating radar data. Dissertation, University of Portsmouth

Coeckelbergh M (2020) Technoperformances: using metaphors from the performance arts for a postphenomenology and posthermeneutics of technology use. AI & Soc 35(3):557–568. https://doi.org/10.1007/s00146-019-00926-7

Davies R, Harty C (2013) Implementing 'Site BIM': a case study of ICT innovation on a large hospital project. Autom Constr 30:15–24. https://doi.org/10.1016/j.autcon.2012.11.024

Davtalab O, Kazemian A, Khoshnevis B (2018) Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. Autom Constr 89:13–23. https://doi.org/10.1016/j.autcon.2018.01.006

Dias W (2006) Heidegger's resonance with engineering: the primacy of practice. Sci Eng Ethics 12(3):523–532. https://doi.org/10.1007/s11948-006-0050-7

Dreyfus HL, Dreyfus SE (1996) The relationship of theory and practice in the acquisition of skill. In: Benner P, Tanner C, Chesla C (eds) Expertise in nursing practice: caring, clinical judgment, and ethics. Springer, New York, pp 29–47

Dunston PS, Shin DH (2009) Key areas and issues for augmented reality applications on construction sites. In: Wang X, Schnabel MA (eds) Mixed reality in architecture, design and construction. Springer, Dordrecht, pp 157–170. https://doi.org/10.1007/978-1-4020-9088-2

Evans RD (2010) Optimising ground penetrating radar (gpr) to assess pavements. Dissertation, Loughborough University

Ewenstein B, Whyte J (2009) Knowledge practices in design: the role of visual representations asepistemic objects. Organ Stud 30(1):7–30. https://doi.org/10.1177/0170840608083014

Fried SJ (2020) Satellites, war, climate change, and the environment: are we at risk for environmental deskilling? AI Soc. https://doi.org/10.1007/s00146-020-01047-2

Friis JKB (2015) Towards a hermeneutics of unveiling. In: Rosenberger R, Verbeek P-P (eds) Postphenomenological investigations: essays on human-technology relations. Lexington Books, London, pp 215–225

Friis JKBO (2017) Gestalt descriptions embodiments and medical image interpretation. AI Soc 32(2):209–218. https://doi.org/10.1007/s00146-015-0615-6

Gao T, Akinci B, Ergan S, Garrett Jr JH (2012) Constructing as-is BIMs from progressive scan data. In: Proceedings Int. Symposium on Automation and Robotics in Construction, 29. IAARC Publications, Eindhoven.

Garbett J, Hartley T, Heesom D (2021) A multi-user collaborative BIM-AR system to support design and construction. Autom Constr 122:103487. https://doi.org/10.1016/j.autcon.2020.103487

Hartmann T, Gao J, Fischer M (2008) Areas of application for 3D and 4D models on construction projects. J Constr Eng Manag 134(10):776–785. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:10(776)

Harty C (2008) Implementing innovation in construction: contexts, relative boundedness and actor-network theory. Constr Manag Econ 26(10):1029–1041. https://doi.org/10.1080/01446190802298413

Hogan T, Hornecker E (2011). Human-Data Relations and the Lifeworld. In: Proc 5th Irish human computer interaction conference. Cork, Ireland

Ihde D (1990) Technology and the lifeworld: from garden to earth. Indiana University Press, Bloomington

Ihde D (2009) Postphenomenology and technoscience: the Peking university lectures. Suny Press, Albany

Ihde D (2015) Preface: positioning postphenomenology. In: Rosenberger R, Verbeek P-P (eds) Postphenomenological investigations:

essays on human-technology relations. Lexington Books, London, pp vii–xvi

Jaw SW, Hashim M (2013) Locational accuracy of underground utility mapping using ground penetrating radar. Tunn Undergr Space Technol 35:20–29. https://doi.org/10.1016/j.tust.2012.11.007

Jeong HS, Abraham DM, Lew JJ (2004) Evaluation of an emerging market in subsurface utility engineering. J Constr Eng Manag 130(2):225–234. https://doi.org/10.1061/(ASCE)0733-9364(2004)130:2(225)

Jol H (2009) Ground penetrating radar: theory and applications. Elsevier Science, Amsterdam

Latour B (1992) Where are the missing masses? The sociology of a Fewmundane Artifacts. In: Bijker WE, Law J (eds) (2000) Shaping technology/building society: studies in sociotechnical change. MIT Press, Cambridge, pp 225–228

Latour B (1996) Actor network theory: a few clarifications. Soziale Welt 47(4):369–381

Li S, Cai H, Kamat VR (2015) Uncertainty-aware geospatial system for mapping and visualizing underground utilities. Autom Constr 53:105–119. https://doi.org/10.1016/j.autcon.2015.03.011

Li X, Yi W, Chi HL, Wang X, Chan AP (2018) A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Autom Constr 86:150–162. https://doi.org/10.1016/j.autcon.2017.11.003

Liberati N (2016) Augmented reality and ubiquitous computing: the hidden potentialities of augmented reality. AI Soc 31(1):17–28. https://doi.org/10.1007/s00146-014-0543-x

Liberati N (2018) Phenomenology, Pokémon Go, and other augmented reality games. Hum Stud 41(2):211–232. https://doi.org/10.1007/s10746-017-9450-8

London K, Pablo Z (2017) An actor–network theory approach to developing an expanded conceptualization of collaboration in industrialized building housing construction. Constr Manag Econ 35(8–9):553–577. https://doi.org/10.1080/01446193.2017.1339361

Lu Y, Li Y, Skibniewski M, Wu Z, Wang R, Le Y (2015) Information and communication technology applications in architecture, engineering, and construction organizations: a 15-year review. J Manag Eng 31(1):A4014010. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000319

Metje N, Atkins P, Brennan M, Chapman D, Lim H, Machell J et al (2007) Mapping the Underworld–State-of-the-art review. Tunn Undergr Space Technol 22(5–6):568–586. https://doi.org/10.1016/j.tust.2007.04.002

Munters GM (2017) Playful mediation of perception and engagement: urban space and location-based augmented reality applications through the lens of play. University of Twente, Enschede

O'Keeffe S, Bosche F (2015) The need for convergence of BIM and 3D imaging in the open World. Proceedings CITA BIM Gathering. Dublin, pp 109–116

olde Scholtenhuis LL, den Duijn X, Zlatanova S (2018) Representing geographical uncertainties of utility location data in 3D. Autom Constr 96:483–493. https://doi.org/10.1016/j.autcon.2018.09.012

Omar T, Nehdi ML (2016) Data acquisition technologies for construction progress tracking. Autom Constr 70:143–155. https://doi.org/10.1016/j.autcon.2016.06.016

Orlikowski WJ, Scott SV (2008) 10 Sociomateriality: challenging the separation of technology, work and organization. Acad Manag Ann 2(1):433–474. https://doi.org/10.1080/19416520802211644

Pătrăucean V, Armeni I, Nahangi M, Yeung J, Brilakis I, Haas C (2015) State of research in automatic as-built modelling. Adv Eng Inform 29(2):162–171. https://doi.org/10.1016/j.aei.2015.01.001

Poulsgaard KS, Malafouris L (2020) Understanding the hermeneutics of digital materiality in contemporary architectural modelling: a material engagement perspective. AI Soc. https://doi.org/10.1007/s00146-020-01044-5

Riemer K, Johnston RB (2014) Rethinking the place of the artefact in IS using Heidegger's analysis of equipment. Eur J Inf Syst 23(3):273–288. https://doi.org/10.1057/ejis.2013.5

Rosenberger R (2013) Mediating mars:perceptual experience and scientific imaging technologies. Found Sci 18(1):75–91. https://doi.org/10.1007/s10699-012-9286-7

Rosenberger R, Verbeek P-P (2015) A field guide to postphenomenology. In: Rosenberger R, Verbeek P-P (eds) Postphenomenological investigations: essays on human-technology relations. Lexington Books, London, pp 9–42

Schweber L, Harty C (2010) Actors and objects: a socio-technical networks approach to technology uptake in the construction sector. Constr Manag Econ 28(6):657–674. https://doi.org/10.1080/01446191003702468

Shatte A, Holdsworth J, Lee I (2014) Mobile augmented reality based context aware library management system. Expert Syst Appl 41(5):2174–2185. https://doi.org/10.1016/j.eswa.2013.09.016

Turk Ž (2001) Phenomenologial foundations of conceptual product modelling in architecture, engineering and construction. Artif Intell Eng 15(2):83–92. https://doi.org/10.1016/S0954-1810(01)00008-5

Verbeek P-P (2005) What things do: Philosophical reflections on technology, agency, and design. Pennsylvania State University Press, University Park

Verbeek P-P (2006) Materializing morality: design ethics and technological mediation. Sci Technol Human Values 31(3):361–380. https://doi.org/10.1177/0162243905285847

Verbeek P-P (2008) Cyborg intentionality: rethinking the phenomenology of human–technology relations. Phenomenol Cogn Sci 7(3):387–395. https://doi.org/10.1007/s11097-008-9099-x

Verbeek P-P (2015) COVER STORY Beyond interaction: a short introduction to mediation theory. Interactions 22(3):26–31. https://doi.org/10.1145/2751314

Walsh SB, Borello DJ, Guldur B, Hajjar JF (2013) Data processing of point clouds for object detection for structural engineering applications. Comput Aid Civ Infrastruct Eng 28(7):495–508. https://doi.org/10.1111/mice.12016

Wellner G (2018) From cellphones to machine learning. A shift in the role of the user in algorithmic writing. In: Romele A, Terrone E (eds) Towards a philosophy of digital media. Springer, Cham, pp 205–224

Wellner G (2020) Material hermeneutic of digital technologies in the age of AI. AI Soc. https://doi.org/10.1007/s00146-020-00952-w

Williams G, Gheisari M, Chen PJ, Irizarry J (2015) BIM2MAR: an efficient BIM translation to mobile augmented reality applications. J Manag Eng 31(1):A4014009. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000315

Wiltse H (2014) Unpacking digital material mediation. Techné 18(3):154–182. https://doi.org/10.5840/techne201411322

Xuesong L, Eybpoosh M, Akinci B (2012) Developing as-built building information model using construction process history captured by a laser scanner and a camera. In: Construction Research Congress 2012: Construction Challenges in a Flat World, pp 1232–1241

Xi W, Hongwei Z, Yinghan Y, Jiajia L, Xiaolong P (2018) Application of BIM Technology in a Large Commercial Complex Project. Journal of Information Technology in Civil Engineering and Architecture, 10(2): 46-51. https://doi.org/10.16670/j.cnki.cn11-5823/tu.2018.02.09