Visualization Techniques in Augmented Reality: A Taxonomy, Methods and Patterns

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Abstract—In recent years, the development of Augmented Reality (AR) frameworks made AR application development widely accessible to developers without AR expert background. With this development, new application fields for AR are on the rise. This comes with an increased need for visualization techniques that are suitable for a wide range of application areas. It becomes more important for a wider audience to gain a better understanding of existing AR visualization techniques.
Within this work we provide a taxonomy of existing works on visualization techniques in AR. The taxonomy aims to give researchers and developers without an in-depth background in Augmented Reality the information to successively apply visualization techniques in Augmented Reality environments. We also describe required components and methods and analyze common patterns.

Index Terms—Visualization, Augmented Reality, Information Visualization, Taxonomy

1 Introduction

Latest developments in *Augmented Reality* (AR) work towards a more accessible technology that is available to end users as well as professionals and opens new fields of applications, such as entertainment or advertisement, but also various other professional applications. This allows developers to create AR applications that overlay digital information into the field of view of users. An example would be digital instructions for a car repair overlaid directly onto the view of this car. In particular, AR frameworks like ARkit[1], ARCore[2] or the Mixed Reality Toolkit[3] make AR experiences more accessible to a wider audience. These frameworks provide registration and tracking techniques that are adequate for a lot of use cases. However, one main challenge remains: the appropriate visualization of content.

Visualization in AR is coming with the challenge of how to integrate digital content with our view of the real world in a combined Augmented Reality view. This challenge is different from the hurdles in traditional visualization techniques where the presented content is well known. In this work, we investigate different ways of how previous research approached the problem of integrating (or compositing) digital content with our view of the real world, which challenges have been addressed, and identify common pathways. The main aim of this work is to provide a better understanding of the general issues for visualization techniques in AR. We specifically aim for a wider audience and not only towards researchers who are AR experts.

We will provide information about the special requirements for visualization techniques in AR, as well as give an overview of the commonly used components and pipelines, common challenges and pitfalls.

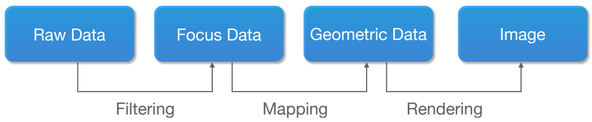

Fig. 1: Scientific visualization pipeline with its three main steps: filtering, mapping, and rendering.

1.1 Visualization

Visualization can be described as the process of converting abstract data into a visual representation that is comprehensible by a human observer. The visualization process itself is often described step-by-step in one of the various versions of the *visualization pipeline* [1]. This allows for subdividing visualization methods into sub methods and provides a better overview and abstraction of these methods.

Normally, the visualization pipeline defines three main steps: filtering, mapping, and rendering as shown in Figure 1. In this concept, the first step, *Filtering*, is a data-to-data mapping that converts *raw data* into *focus data*, for instance by producing a smaller subset of the raw data set. *Mapping* is the second step and uses the focus data to generate geometric information. An example are data points that are

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1. https://developer.apple.com/documentation/arkit
2. https://developers.google.com/ar/
3. https://microsoft.github.io/MixedRealityToolkit-Unity/

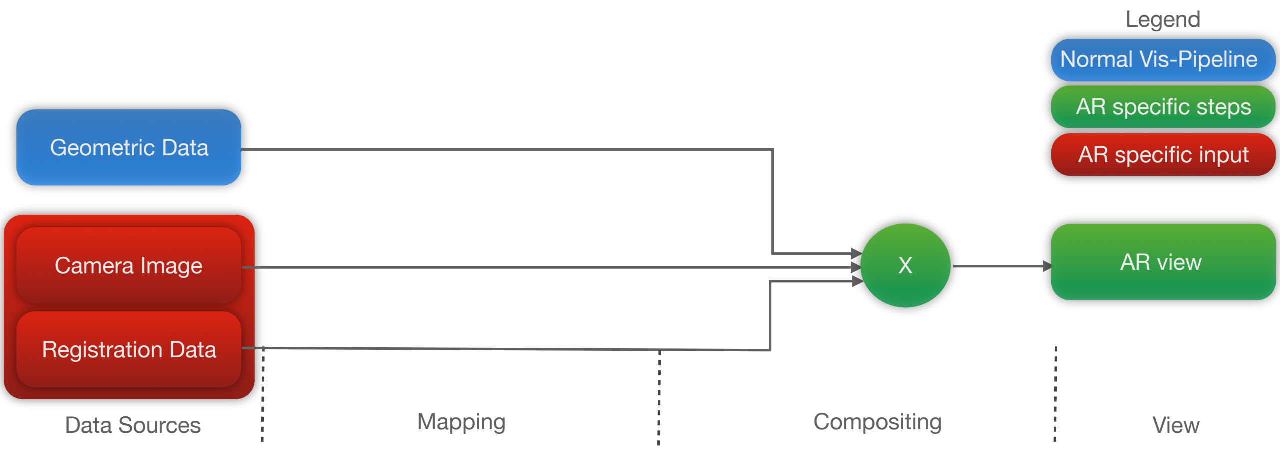

Fig. 2: AR Visualization Pipeline illustrating a naïve overlay using predefined geometric data, a camera image and registration data for creating the compositing.

mapped to 2D points or a line with a specific color. The last step is the *Rendering* of this geometric data to produce a 2D image that can be display on an output device. It is important to highlight here that rendering is seen as one step of the visualisation process. To keep to the scope of the paper we will not cover any techniques that are specific to the rendering step, such as photo-realistic rendering. This is a common separation, e.g. [2] stating "Visualization: research into methods that use AR to make complex2D/3D data easier to navigate through and understand." vs. "Rendering: research into techniques for computer graphics rendering; and other sensory modalities."

1.2 Visualization in AR

In contrast to visualization in *Scientific Visualization* and *Information Visualization*, visualization in AR is usually defined in a different way. Available definitions focus more on the fact that not only virtual data is mapped to a visual representation, but also on spatial relationships and interaction between the physical world and raw (virtual) data [3], and how they are combined to generate the final 2D image. Generally speaking, an important aspect of visualization in AR comes from Azuma's definition of AR [4]: the combination of real and virtual information.

This means if we want to use the traditional visualization pipeline in the context of AR visualizations, it has to be modified to reflect this combination of real and virtual information. Azuma amended his original survey by emphasizing how AR systems need to have a good registration process to align virtual and physical objects well [5]. By adding registration information, a camera image (representing the environment in video see-through AR interfaces and for extracting environment information captured in the image) and a dedicated *compositing* step to the original pipeline, we can adapt it to reflect the characteristics of AR visualization in a naïve AR visualization pipeline (Figure 2). In particular, here it is important to mention that the original rendering step is replaced by a compositing step that addresses the need to combine data from different sources relevant to the AR visualization. Overall, we can say that visualization in AR differs from the traditional definitions of visualization because it is a combination of the data to display with information that is part of the actual physical environment of a user.

It should be noted at this point that this work intentionally excludes issues and challenges that are unique to specific AR displays (e.g Spatial AR, video see-through displays, optical see-through displays). Realizing an AR interface for example using an optical-see through display will come with its own challenges because of the characteristics of the usually half-transparent display [6], [7], [8]. A general overview of some of these display specific issues can be found in other works [9], [10].

1.3 Challenges

At first glance, the implementation of the additional requirements that come with the combination of virtual data and the physical environment of the user seems to be straight-forward if the registration between virtual content and the physical world representation is known (for instance in terms of a camera transformation matrix). In this case, data can be combined by simply overlaying the registered virtual content to the user's view. However, in a lot of situations, a compositing using such a naïve overlay can lead to serious perceptual problems that may prevent the user from comprehending the visualization.

For instance, one of the problems that often arises in AR when visualizing virtual objects using a naïve overlay is missing visual coherence [9]. In this case, the virtual content is not coherently integrated into the AR view. This can happen when perceptual cues are interfering with each other or are missing. This is

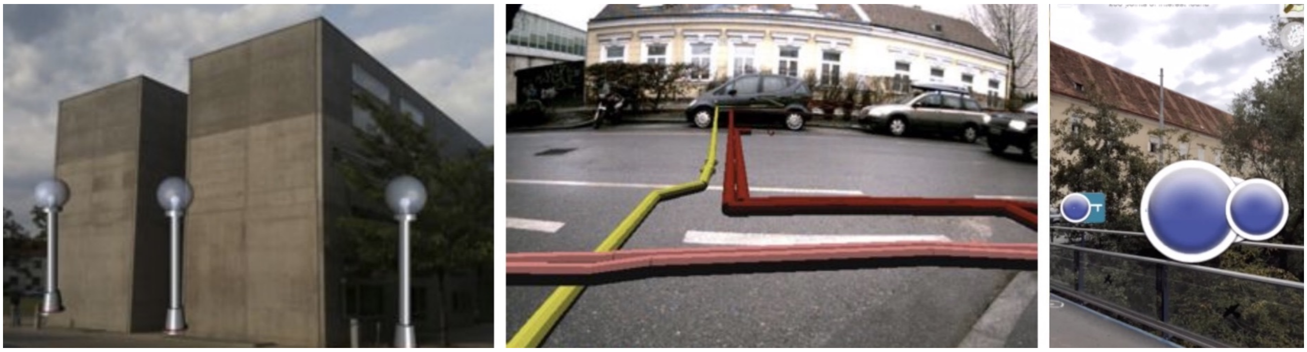

Fig. 3: Visualization problems caused by naïve compositing functions. Left) Virtual planned lamps are perceived to be located in front of the house not next to it. Middle) Virtual pipes seem to float above the ground. Right) In this tourist scenario the naïve overlay of sight labels produces information clutter.

a major challenge, since users need these perceptual cues to understand the spatial relationships between virtual data and real world. If, for example, the compositing method does not take occlusions between virtual and physical objects into account, it will result in wrong depth perception. The virtual objects will always be seen as being in front of the physical world objects. Figure 3 (Left) demonstrates this problem within an AR planning application. Planned lamps are superimposed on video images to allow users to experience what it would look like if the lamps were real. Unfortunately, the missing shadows and occlusion cues lead to the wrong perception of floating virtual lamps and a lack of coherence.

A similar problem occurs when using a simple overlay to visualize information that is naturally invisible such as in popular X-Ray visualizations utilizing an AR interface [11]. In Figure 3 (Middle), several subsurface pipes visualized in a X-Ray view are shown. Since the pipes are just naïvely superimposed on the video image, there is a lack of natural depth cues. Instead of being perceived as being located subsurface, the pipes seem to float above the ground and making it difficult for the user to judge where exactly they are located.

As those examples show, AR visualization techniques have to address these challenges that arise from combining virtual and real data, objects, and environments.

1.4 Contribution

The main aim of this work is to provide an overview of important components for AR visualization, existing techniques and discuss common pattern. For this purpose, we investigated existing AR visualization techniques. We explain their components and look into ways how to classify and group existing methods. While in *Scientific Visualization* and *Information Visualization* it is common to use the *Visualization Pipeline* for mapping the different steps of a visualization technique, in AR these traditional pipelines are not working because of the amount and different types of inputs (such as the digital data, and the information from the physical environment) that are involved in an AR visualization. Overall, the main contributions of this work are

- the identification of important components for realizing an AR visualization,
- the visualization pipelines adapted to the special needs of AR,
- a taxonomy that structures existing visualization techniques,
- and the identification of common patterns (pipelines).

2 Related Work

While visualization and interaction techniques for virtual environments have been researched intensively [12], [13], [14], [15], there is only limited related work that classifies and analyses visualization techniques for AR. There has been some previous work on surveys and literature review of AR in general [16], [2], [17], [18]. These works provide surveys of papers and topics in the field of AR in the last 15 to 50 years. There are also surveys published for more specific topics such as applications of AR [19], or perceptual problems in AR and visual coherence [10], [9]. However, for the topic of visualization in AR, only minimal work is available.

Willet et al. defined general concepts of data representation and presentation for AR and looked into relationships between data, physical environments, and data presentations [20].

In 2011, Kalkofen et al. provided an overview of AR visualization techniques [3]. Their work provides a comprehensive overview of existing visualization techniques and identified main topics such data integration, scene manipulation and context driven visualization. While their work provides a good overview of visualization techniques for AR, so far there is no investigation of common patterns, pipelines or classification of AR visualization techniques. In this work we want to bridge this gap and provide a closer look into existing pipelines to identify patterns, similarities and challenges specific to AR while also integrating many newer works that have not been considered by Kalkofen et al..

3 Data Collection

To gather research within the field of visualization methods in Augmented Reality, we used a defined set of search criteria. We made use of the two main databases within the field (the IEEE Xplore database, and the ACM library).

We used the following paper gathering strategy:

1) Find *Augmented Reality* and *Visualization* in title
2) Find *Augmented Reality* in keywords and *Visualization* in title
3) Find *Augmented Reality* and *Visualization* in authors keywords.

This search resulted in a total number of 429 different works. From these works, we removed all those works that were not introducing an AR visualization technique (e.g. works that were using AR visualization for a specific application scenario or focusing on interaction techniques, as well as works that were purely on user studies, work on virtual reality, republished content, as well as non-English works, Awards, Table-of-Contents, Keynotes, Demo abstracts). After filtering we ended up with roughly 40 works that potentially present new visualization techniques. From there we filtered even more strict removing works that have no visualization technique specific to AR, for instance such as works that are applying standard information visualization in AR without any specifics to AR (e.g. [21], in total 13). After this initial data collection we also queried for papers combining Augmented Reality and *Rendering*. Despite the more than 1000 results this query added only two additional papers within the scope of this work. Finally, given our expertise in the field we added missing important related works that were lacking keywords in the databases (e.g. many older works) and double-checked for references within the identified papers. In total we ended up with 67 works that present new AR visualization techniques.

4 AR Visualization Components

Based on the information from the gathered research works, we identified several reoccurring components that were used by most of those works. These components include the camera image, registration data, geometric data, and often some form of masking data.

Camera Image (I): A camera is an essential component in most AR systems independent of the used AR display (e.g. video see-through or optical see-through). The camera image captures the real environment around the user and is often used for visual tracking. Moreover, the camera image is essential when using a video see-through (VST) approach where the real environment is shown to the user as a live video feed with minimal latency. However, also when using optical see-through displays the camera image provides many important information for example when extracting saliency information or other image cues.

Registration Data (R): Registration data plays a major role by supporting the alignment of virtual and physical objects. Registration in the AR context is the spatial relation between the virtual objects and the real environment [22]. Registration data can be provided by different means, e.g. six-degrees-of-freedom tracking systems, AR fiducial markers [23], vision-based tracking [24], [25], [26], image recognition-based detection or sensor-fusion supported geo-referenced registration data obtained (e.g. [27]).

Geometric Data (G): Geometric data is the data that is not physically present within the user's environment. It ranges from 2D data such as labels, over 2.5D data such as billboards to 3D data such as 3D models. It will be the task of the application to use the relevant registration data to ensure the geometric data is properly displayed with high level of accuracy in terms of alignment.

Context Data (C): In addition to the geometric data that we want to visualize, data that represents aspects of the physical environment is considered as context data. Context data is an important component as it supports the combination of virtual data with the physical environment.

For instance, this could be a phantom model that is used for creating correct occlusions in 3D space or a context mask (image mask) that represents important areas of the physical environment and that is used to highlight a certain area in the camera-image space.

For context data it is important to note that it can be a static representation (e.g. by a CAD model) or a dynamic representation that continuously updates the representation of the physical environment (e.g. RGBD data stream or a point cloud) and as such context data is related to context data that can be obtained from sensors in the environment and which is also increasingly used in AR for context awareness [28].

Coordinate systems: It is important to note that all the described components come with their own coordinate reference systems. These coordinate systems can be , model-centred, world-centred, sensor-centred, user-centred, camera-centred. For instance, the geometric data may be defined with a model-centred space, the physical representation data may be coordinated with a capture devices such as a Kinect, the camera image is defined as 2D image and comes with its camera centred coordinate system and the registration data could be aligned to a tracking device. The existence of multiple coordinate systems comes with its own challenges of mapping between the different coordinate systems. This mapping step is part of the AR visualization pipeline.

5 AR VISUALIZATION TAXONOMY

In order to identify common pipelines and patterns of visualization techniques in AR, we started creating a taxonomy of AR visualization techniques. Such a classification contributes to the understanding of similarities and differences between different techniques and will also help to identify common patterns.

Previous work focused on classifying perceptual problems in AR [10]. However, to our knowledge there is no work on classifying the characteristics of visualization techniques in AR to date. Elmquist et al. [15] did a classification within the area of 3D occlusion management for virtual environments. They described the design space of 3D occlusion management using a set of identified domains. Based on the design space, they then proposed a classification of 3D occlusion management techniques and used it to classify 50 different techniques. They used their taxonomy to identify areas that are not covered by existing techniques. Likewise, the introduction of a taxonomy for visualization techniques in AR can help us to identify gaps for visualization in AR.

We follow Elmquist's work by defining the design space of AR visualization using a set of dimensions. Similar to Elmquist's work, for each dimension we identified a set of domains that characterize the dimension. Each visualization technique is then mapped to a domain within each dimension. This allows us to define a consistent language and to classify the techniques. By analyzing the related work, we identified the following common reoccurring dimensions:

- Purpose - What is the main goal that this visualization technique is achieving?
- Virtual Data Visibility - Is the virtual data directly visible, or are there any occlusion or X-Ray view techniques used?
- Virtual Cues - Is the visualization technique integrating any virtual cues to support the AR visualization?
- Filtering - Is the data presented unfiltered or is filtering used to reduce the amount of data?
- Abstraction - Is the raw data visualized or is there any additional step to provide a degree of abstraction/changed representation of the input data?
- Compositing - How is the combination of real and virtual input achieved?

5.1 Purpose

A common goal of AR visualization techniques is to improve the presentation of virtual content being integrated into the physical world. However, there are different aspects each visualization technique addresses primarily. From the related work, we found that those aspects mostly focus on a) achieving visual coherence, b) a better depth perception, c) reducing information clutter, d) supporting exploration, and e) directing attention.

a) Visual Coherence - Visual coherence in AR often focuses on a convincing integration of virtual content into the physical world. Often, AR applications are lacking of visual coherence due to missing depth cues, such as occlusions or shadows. In order to address this problem, researchers in AR proposed various techniques that achieve visual coherence by extracting and using natural cues from the physical environment[29], [30], [31], [32], [33].

We are referring to these natural cues as physical cues, since they can also be found in the physical world. These cues try to mimic the natural behavior of physical objects for virtual objects. The main goal is to achieve visual coherence based on the assumption that our visual system knows how to process these cues.

b) Depth Perception - Depth perception for humans is complicated if the objects do not follow expected principles [34]. This is often the case in AR, it may happen when visualizing occluded objects, floating objects, or in general objects that are too abstract to hold normal physical characteristics. This is related to visual coherence. In order to support the depth perception in AR, additional cues are required. We refer to these cues as *virtual cues*, since they are not naturally available in the physical world. In the literature, they are also called *graphical aides* [35]. AR visualization methods have to integrate these cues additionally.

c) Clutter reduction - With the increasing amount of omnipresent information, the presentation of it is more likely to become subject to clutter. Consequently, researchers in the field of HCI and Information Visualization investigate the issue of information clutter for a long time. In 2005, Rosenholtz et al. provided a definition of clutter in visualization systems:

> "Definition: Clutter is the state in which excess items, or their representation or organization, lead to a degradation of performance at some task." [36]

In the research field of Information Visualization several techniques have been developed that aim to reduce information clutter, such as filtering the amount of objects or view distortion techniques that allow to magnify or rearrange objects of interest.

In AR visualization, complex data is often embedded in complex physical environments that are crowded with information by nature. Thus, information clutter is a big issue in AR visualization. In order to address this problem, researchers introduced methods that focus on the problem of information clutter in AR environments. Similar to the methods available for Information Visualization, research groups proposed methods that either reduce the amount of information by filtering the presented content or by using spatial distortion techniques to rearrange the objects in a more comprehensible way.

d) Exploration - Another objective that has been addressed by AR visualization techniques is the exploration of content or environments. There are several visualization techniques that support the task of exploration, for instance by providing additional information for comparison [37] or by providing contextual information for exploring a scene [38].

e) Attention direction - Directing the attention of users in a certain way is another ability that AR visualization techniques can achieve. For instance, by masking or highlighting certain areas they can direct more attention to a desired region of interest.

Domain: Visual coherence, depth perception, clutter reduction, exploration, attention direction

Example Techniques:

Visual coherence [30], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [32], [49], [31], [50], [51], [52], [53], [54], [55], [33], [56], [57],

Supporting depth perception: [58], [59], [60], [61], [62], [63], [64], [65], [35], [66], [67], [68], [69], [70],

Reducing information clutter [71], [72], [73], [74], [75], [76], [77], [66], [78], [79], [80], [81],

Exploration [82], [37], [83], [84], [38], [85], [86], [87], [88], [89], [90], [91]

Attention direction [92], [93], [94], [95], [96].

5.2 Visibility of Virtual Data

The visibility of virtual data has an influence on the visualization problems that need to be solved. Virtual data can be completely or partially occluded by physical objects, or be completely visible or even out of view. This is particularly evident in the visualization of invisible data, so-called X-Ray visualization [97], [50], [31], [11]. X-Ray views are popular techniques in AR and are used for various applications such as subsurface visualization [31] or medical applications [47]. This kind of visualization has special challenges in terms of visual coherence, since some of the natural depth cues are not available. Thus, the visualization of occluded and semi-occluded virtual data is strongly related to the primary goal of visual coherence. This is also reflected in the parallel set visualization of related works where a large amount of works that have the visual coherence as primary purpose work with occluded and partially occluded virtual data (Figure 5, blue stream). In contrast, for the visualization of visible virtual data the visualization purposes are more diverse covering aspects of depth perception, information clutter, exploration and attention direction. In addition, virtual data can also be out of view with visualization techniques focusing on guidance to these out of view elements.

Domain: Occluded, Partially occluded, Visible, Out-of-view

Techniques:

Occluded: [58], [59], [61], [64], [65], [66], [67], [68], [82], [72], [74], [76], [77], [66], [47], [32], [49], [31], [50], [51], [52], [33], [56]

Partially occluded: [30], [39], [41], [42], [43], [45], [46],

Visible: [92], [93], [94], [95], [96], [60], [62], [63], [35], [69], [70], [37], [83], [38], [85], [86], [87], [90], [91], [71], [73], [75], [78], [79], [80], [81], [40], [48], [53], [54], [55], [57].

Out-of-View: [84], [88], [89].

5.3 Depth Cues

As highlighted by Elmquist et al. depth cues have a major impact on the users' understanding of their environment [15]. Because of this, Elmquist et al. captured the degree of depth cues within their taxonomy for 3D Occlusion Management. As shown by previous work [98], [11] depth cues have also a strong impact on the spatial understanding within AR. In contrast to Elmquist et al.'s work that captured the degree of depth cues we decided to capture their characteristics specific for AR by using the following three main options: Physical cues, virtual cues or no additional cues.

a) Physical cues - We define physical cues as cues that try to mimic or rebuild natural pictorial depth cues, such as occlusion or shadows. They can be computed from different information sources that contain contextual information about the physical and virtual world. For instance, edges can be extracted from the camera image and used as natural occlusion cue.

b) Virtual cues - We define virtual cues to be graphical aids that are naturally not available in the physical world such as virtual scales, measurements or other graphical hints.

Domain: none, physical, virtual

Example Techniques:

None: [65], [82], [72], [76], [77], [66], [92], [94], [95], [96], [37], [83], [38], [85], [86], [87], [91], [71], [73], [75], [78], [79], [80], [81], [40], [48], [53], [54], [55], [57]

Physical: [47], [32], [49], [31], [50], [51], [52], [33], [56], [30], [39], [41], [42], [43], [45], [46], [90]

Virtual: [58], [59], [61], [64], [66], [67], [68], [74], [84], [88], [89], [93], [60], [62], [63], [35], [69], [99], [70]

5.4 Abstraction

Abstraction in a visualization context allows for the reduction of visual complexity by finding different representations while preserving only the relevant data. This definition is close to the one of Strothotte [100] who define abstraction as *the process in which complex information is refined to signify the importance of certain features from the underlying model to provide better context and visualization*. Abstractions allow us to reduce the amount of information showed by mapping or visualizing through a wide range of alternative representations. We differentiate between techniques that display the concrete data and techniques that modify the visualization using an abstraction of the data. In AR one of the challenges is to find a suitable amount of abstraction that is still coherent with a not abstracted version of the real environment.

Domain: Concrete , Abstract

Techniques:

Abstract: [96], [78], [79], [80], [70], [95], [83], [86], [87], [84], [88], [89], [60], [69].

No abstraction: [65], [72], [66], [74], [82], [76], [77], [92], [94], [37], [38], [85], [91], [71], [73], [75], [81], [40], [48], [53], [54], [55], [57], [47], [32], [49], [31], [50], [51], [52], [33], [56], [30], [39], [41], [42], [43], [45], [46], [90], [58], [59], [61], [64], [66], [67], [68], [93], [62], [63], [35].

5.5 Filtering

Simple AR visualization methods, usually apply no filtering and render a predefined geometric model in a naïve overlay. When it comes to the visualization of more complex data, an adequate filtering is required to avoid information clutter. In particular, information clutter is increased in outdoor environments due to the complexity of the physical environment. We can divide the dimension into techniques that use raw data and techniques that apply filtering.

Domain: Raw, Filtered

Techniques:

Raw: [82], [76], [77], [92], [94], [95], [37], [83], [38], [85], [86], [87], [91], [71], [73], [75], [81], [40], [48], [53], [54], [55], [57], [47], [32], [49], [31], [50], [51], [52], [33], [56], [30], [39], [41], [42], [43], [45], [46], [90], [58], [59], [61], [64], [66], [67], [68], [84], [88], [89], [93], [60], [62], [63], [35], [69].

Filtered: [65], [72], [66], [96], [78], [79], [80], [74], [70].

5.6 Compositing

The way the virtual and the physical information is composed into the final AR view depends on the AR display (e.g., optical see-through, video see-through, spatial AR) but also depends on the objectives of the visualization. As discussed in the beginning, this paper focuses on the visualisation technique and tries to abstract the AR display as much as possible. However, we acknowledge that many existing techniques were presented within video see-through systems and some compositions are harder to realise in optical see-through systems as parts of the compositing are happening in the optical combiner. With respect to the visualisation, we differentiate between techniques that use a simple overlay, blending (or masking if the context mask is binary), information transformation, or inpainting.

a) Overlay - Overlay describes all techniques where the virtual geometric data G is simply superimposed on the physical world representation. For simplicity, we discuss this here in the context of a video see-through display where the physical world is captured by the camera image I. When considering optical see-through devices much of the compositing is happening in the optical combiner where I is basically the environment light representing the physical world. The combination of the environment I and virtual content G defines the final compositing $O = G + I$.

d) Blending - Instead of simply combining virtual content and real content, blending techniques use a blending parameter to control how virtual and physical content is combined. They use a blending mask (or context mask) M to control which virtual and which physical information is visualized or omitted and to which amount. The mask information is usually extracted from the context data (C) The final compositing is then given by $O = MG + (1 - M)I$. When M is represented by binary values the compositing is a masking, when values range between 0-1, the masking process becomes a blending. Blending combines content by using a weight in the compositing step and can even be used for achieving a multi-layered blending by using multiple weighting masks (M_i).

b) Transformation - The transformation (T) of information is a compositing technique that either spatially manipulates physical or virtual items or manipulates their appearance for visualization purpose. These techniques create the final compositing by $O = T_G(G) + T_I(I)$ and depend on the transformation of virtual content T_G and of physical content or context information T_I.

c) Inpainting - Inpainting is the process of synthetically reconstructing parts of the video image that were lost due to occlusion from undesired objects such as markers or robot arms. It often involves a manipulation of the camera image and does not affect the virtual geometries $O = IN(I) + R(G)$.

Domain: Simple Overlay, Blending(Masking), Transforming Information, Inpainting

Example Techniques:

Simple Overlay: [80], [70], [83], [86], [87], [84], [88], [89], [60], [69], [72], [66], [38], [85], [91], [73], [40], [54], [55], [90], [64], [66], [68], [93], [62], [63], [35],

Masking/Blending: [96], [95], [65], [74], [82], [92], [71], [47], [32], [49], [31], [50], [51], [52], [33], [56], [30], [39], [41], [42], [43], [45], [46], [58], [59], [61], [99]

Transformations: [78], [79], [76], [77], [94], [37], [75], [81], [57], [67]

Inpainting: [53], [48].

5.7 Summary

By investigating the similarities and differences of visualization techniques within the related work, we identified a set of dimension and their domains to classify existing AR visualization techniques (Figure 4). Plotting the visualization techniques sorted along to those dimensions and domains gives an overview of the distribution of common pathways and design choices.

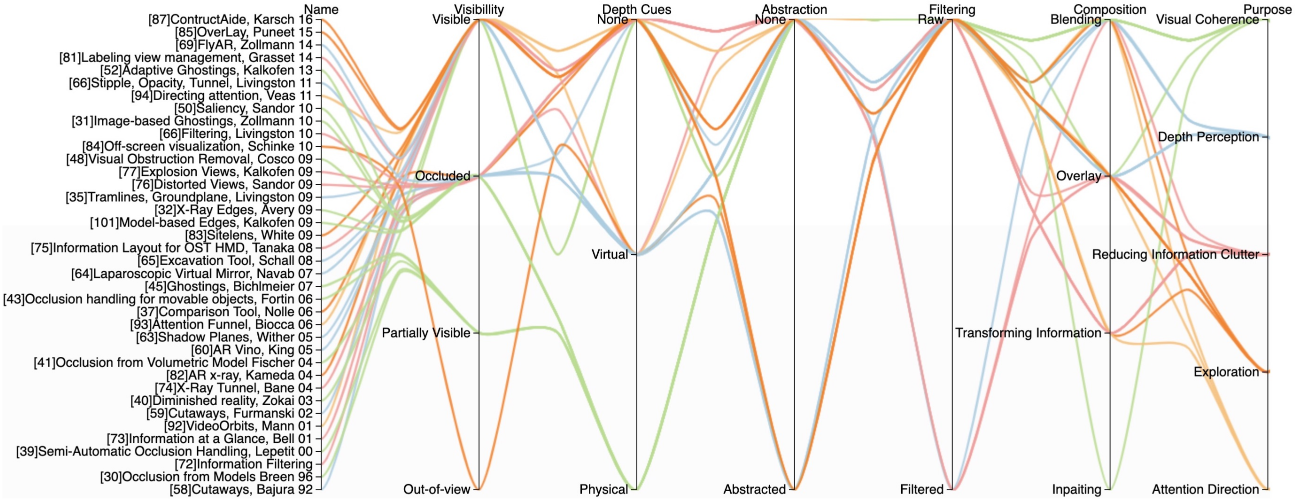

Fig. 4: AR visualization techniques mapped to the taxonomy (limited to publications with citation counts above 30 according to Google Scholar, Feb. 2020). Interactive online version available with all publications. [101].

The grouping in Figure 5 of the classification brings up a few interesting aspects. First, it shows that visualization techniques used for occluded and partially occluded data in AR are either focusing on visual coherence or on depth perception. While for the partially occluded data, the nearly exclusive purpose is to achieve visual coherence (often using physical depth cues); for completely occluded data the primary objective is more diverse, but also has a strong focus on visual coherence or depth understanding.

We can further see that some dimensions have an equal distribution in their domains, while others seem to be clustered to one domain. For instance, the usage of physical, virtual and no cues is nearly equally distributed. In contrast, only a small number of techniques apply a filtering technique (14%). With the continuous growth of available data in general, we assume that aspects of information filtering specific to the needs of AR will become more important in the future.

Another important aspect that becomes evident from our classification is the relationship between main purpose and data visibility, depth cues, filtering as well as compositing. Firstly, it seems that most visualization techniques that support depth perception use simple overlays of virtual depth cues and no filtering. Improving the depth perception seems to be of interest for visible as well as for occluded information. Secondly, visualization techniques that aim to support seamless visual coherence are often used in the context of occluded and partially visible virtual information. In contrast, visual coherence in the context of visible virtual information has only been explored by a few works. However, we assume that with an increasing level of fidelity of virtual models the need for addressing visual coherence for visible virtual data will increase.

In order to integrate hidden virtual information in the compositing, most visualization techniques apply a blending method.

Another interesting aspect that our classification shows is that filtering techniques are not that exclusively used for reducing information clutter as one would expect, they are also used for supporting depth understanding and attention direction.

6 Design Patterns: AR Visualization Pipelines

Based on the classification in the taxonomy, we identify which visualization techniques often used for which visualization purpose and which kind of visualized data. In this section, we use our dimensional space to refine the traditional visualization pipeline for AR that we described in the introduction. Our AR visualization pipeline provides a simplified representation of the visualization process. To be able to represent the complete classification of exiting techniques, we describe different implementations of the AR pipeline, each addressing different visualization problems.

As mentioned before, for simple AR scenes that contain no occlusion and no complex data, a simple overlay compositing can be used that combines a defined registered virtual geometry with the environment (e.g. as video image in video-see through or via the optical combiner for optical-see through, Figure 2). Examples for this kind of visualization are the Magic Book where virtual content is overlaid over a book (video see-through) [103] or the visualization within the Touring Machine (optical see-through) [104].

The simple pipeline is not working for more complex situations with partially or completely hidden, or complex information. As identified in the taxonomy, several research groups developed methods that aim to increase the comprehensibility in these situations.

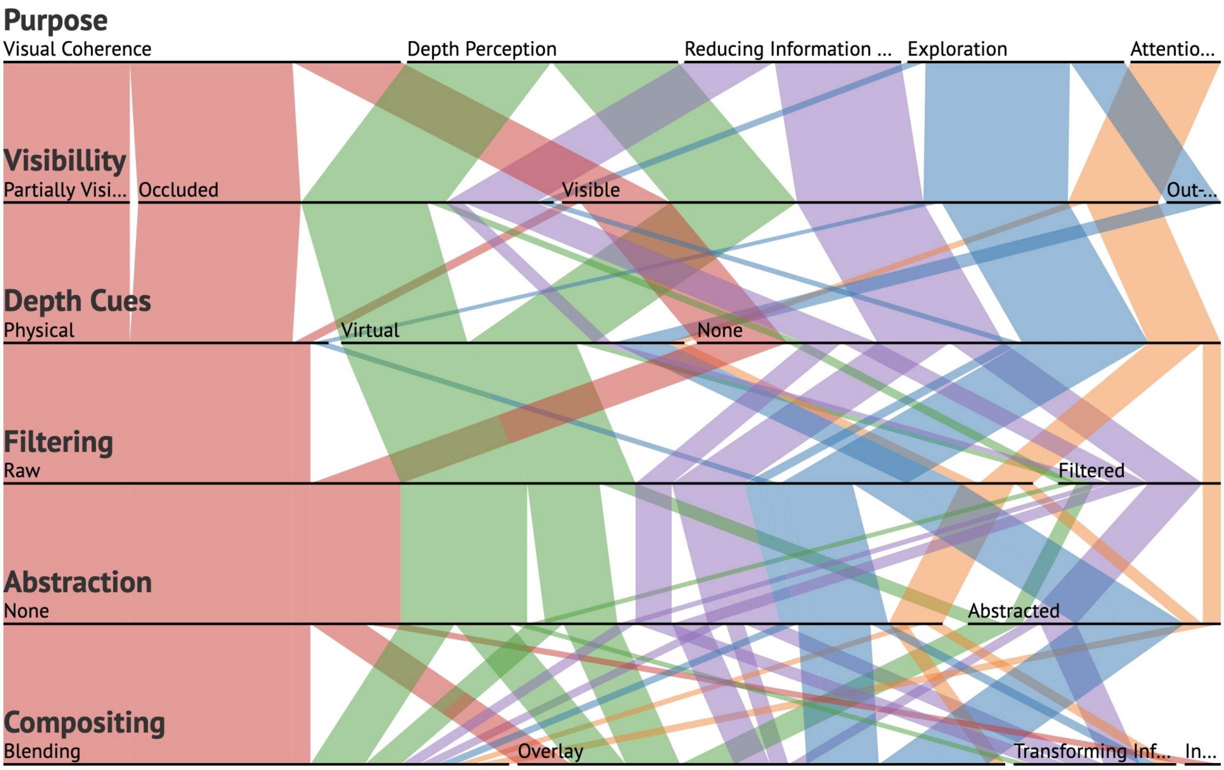

Fig. 5: Grouping of AR visualization techniques in a parallel set visualization. Please note that there is a different order of domains compared to the text due to grouping reasons to highlight the clustering between different streams Interactive online available version [102].

Our taxonomy shows that these objectives are achieved by adding, removing or transforming different kinds of information. This requires that we adapt the visualization pipelines for the different needs.

We used the taxonomy also to identify frequently used pipelines. These pipelines can be used as design recommendations for future research.

Fig. 6: Using visual saliency extracted from a camera image for providing physical depth cues in an X-Ray view of underground pipes (left) and a virtual room (right) (Zollmann et al. [11].)

6.1 Physical Depth Cues Pipeline

The strongest stream represented by 18 works is addressing visual coherence using a blending of physical depth cues. This design pattern is used mainly for occluded and partially occluded virtual data. The physical depth cues are used as context data and can either be image-based or model based or a combination of both depending on where they are extracted from.

6.1.1 Image-based Physical Cues

Image-based techniques achieve visual coherence by extracting physical cues from video images. They can be used for creating physical cues in situations where the depth order of virtual and physical world is known (for instance through a semantic meaning as we have it for the visualization of subsurface infrastructure) and no accurate and precisely registered 3D model of the occluding physical world object is available (Figure 6 Left). Since such an accurate model of the physical context may be not available in every scenario, image-based techniques focus on creating physical cues based on 2D physical world data giving by the camera image. In Figure 7, we show the process of extracting physical cues from the camera image using the our adapted AR visualization pipeline. The AR pipeline reflects how important elements from the camera image are filtered and mapped to an context mask (Figure 7, (Left)). These context masks are then combined with the camera image and virtual geometries to create the final AR visualization using blending.

Such an approach has been introduced by Kalkofen et al. [105]. In their work, they extracted edges from a camera image and used them to create edge-based ghostings. In this approach, the edges are rendered on top of the video image and the virtual content. The AR

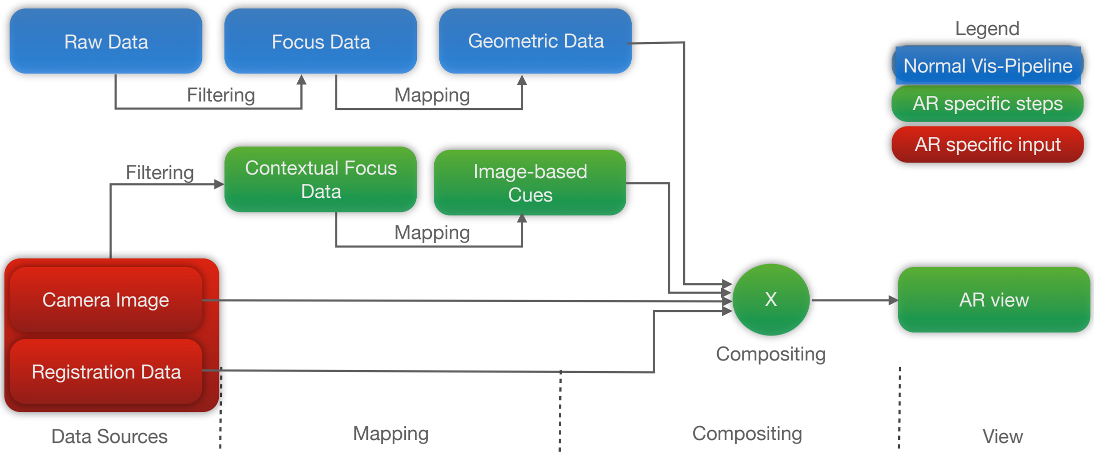

Fig. 7: AR visualization pipeline for extracting image-based physical cues. (Data sources) Important elements from the camera are extracted and (Mapping) mapped to an importance map that represents the physical cues. (Compositing) These cues are then combined with the camera image (for video see-through) and virtual geometries to create the final AR view.

visualization pipeline in Figure 7 reflects this: 1) the camera image is used to extract edges as contextual focus data (filtering), 2) the edges are mapped to a ghosting mask that is 3) used in the final compositing step. Bichlmeier et al. extended this approach by using a combination of edges and bright pixels as physical depth cues [106]. Another approach that uses edges as input to create physical cues is the method of Avery et al. [32]. They applied edges to improve their X-ray vision system in outdoor environments. Based on this work, Zollmann et al. as well as Sandor et al. later on defined the physical cues as being saliency information [50], [31]. They computed saliency masks from the camera image and the layer of virtual content to decided which information should be preserved in the final rendering (Figure 6). All these methods work well in situation were enough meaningful data is available in the camera image, but will fail for poorly textured scenes.

6.1.2 Model-based Physical Cues

If a model representation of the environment is available, this representation can be used to derive pictorial cues. In Figure 8, we depict our AR visualization pipeline using contextual data to derive cues for the scene integration. Contextual data as additional data source is only useful, if an accurate 3D registration and meaningful models are available.

Some approaches use contextual data directly for occlusion culling to provide occlusion cues. One of the earliest approaches in this field used an interactive method to manually align models of physical world objects and applied these models for occlusion culling [30]. Fiala combined a 3D model of the occluding object and marker tracking for occlusion culling [44]. Breen et al. also proposed to use stereo vision to create a 2.5 depth map for occlusion culling [30]. A similar approach was applied by Fischer et al., who used dynamic 2D camera and background information [107] or a time-of-flight camera to create a depth map as input for occlusion culling, respectively (Figure 9, Left) [108].

More recent approaches use 3D models of the physical environment for increasing the visual coherence in X-Ray AR by deriving physical cues from the geometric or visual properties of the model. For instance, Lerotic et al. [109] presented an approach to maintain salient details of an occluder model from a pq-space-based non-photorealistic rendering. Bichelmeier et al. used ghostings from registered volumetric data to improve depth perception in AR applications in cases where hidden structure is of interest [45]. For this purpose, they used the curvature, the angle of incidence and the distance falloff to compute the final transparency in the ghosting. Kalkofen et al. demonstrated how to create ghostings based on an analysis of registered 3D CAD models [105] ((Figure 9, Middle)).

These last three model-based approaches for X-Ray visualization only work well if the models of the occluding object show interesting features in their geometry. Mendez and Schmalstieg presented an approach that allows to create comprehensible ghostings for rather simple shaped and sparsely textured physical objects [110]. By mapping a predefined importance map on the model of the occluding physical object, selected areas of the physical object can be preserved (Figure 9, Right).

However, existing model-based approaches focus nearly exclusively on static environments, since in this case it is easier to either build a model of the environment or capture it.

6.1.3 Combining Model-based and Image-based Physical Depth Cues

Another method is to complement the depth cues with both model-based cues and image-based picto-

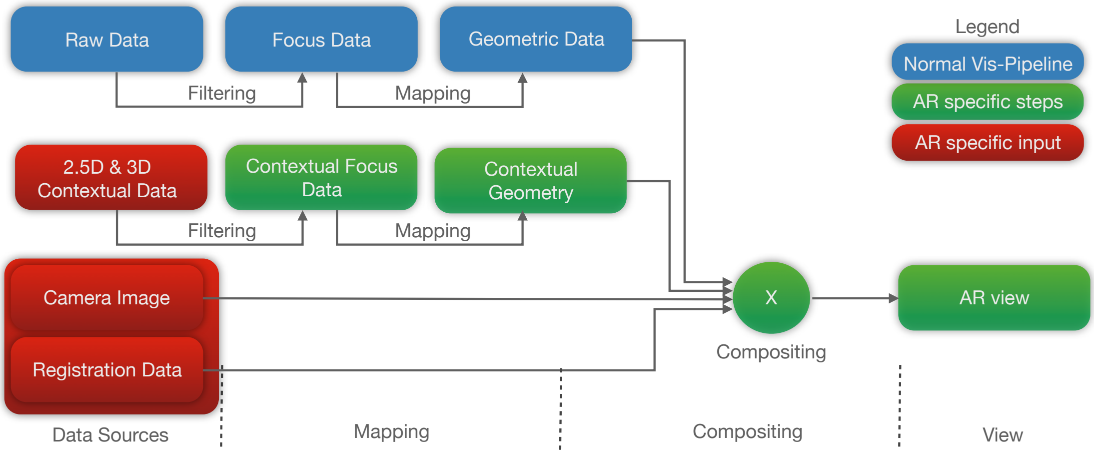

Fig. 8: Pipeline for creating model-based physical cues. A 2.5D or 3D representation of the physical world is used as additional input for the visualization to create physical cues. The camera image is only needed for video see-through displays or when extracting other image features.

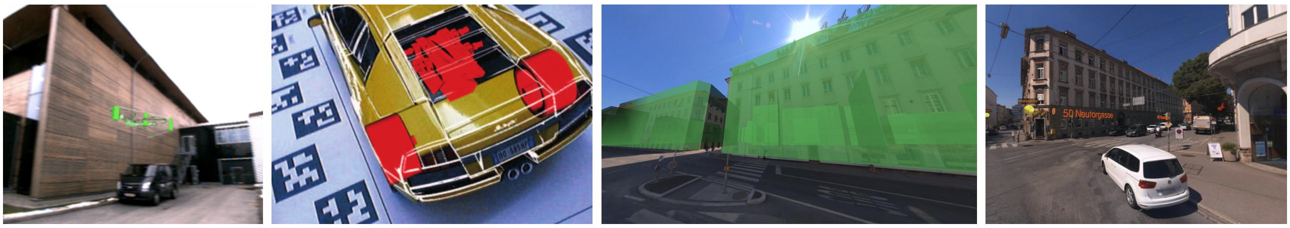

Fig. 9: Examples for using model-based physical cues. Left) Using aerial 3D reconstruction data for occlusion culling (Zollmann et al. [69]). Middle Left) A ghostings based on edges extracted from a registered 3D CAD model (Kalkofen et al. [105] ©[2009] IEEE). Middle Right) GIS data used for occlusion culling. Right) GIS data applied for occlusion culling (Skinner et al. [70])).

rial cues. Rather than relying on either the model-based cues or pictorial depth cues, a merge of both could provide more accurate representation of the environment, decreasing the chance of visualization appearing unintentionally in wrong locations. An example of a combined method is a depth map estimation done by combining sparse 3D models from GIS database with the existing images and videos [111]. This method uses the segmented images and with the aid of the sparse models, able to estimate depth and planes which in return is useful for visualization such as annotations, surveying or placement of virtual items. As mentioned in the previous section, outdoor model-based cues are of higher difficulty to produce due to the complexity but with a combination of both methods it greatly improve performance.

6.2 Virtual Depth Cues Pipeline

The second largest stream (14 works) are visualization techniques that use an overlay of additional virtual depth cues. In this context we can differentiate between methods that use geometrical virtual depth cues or appearance based virtual depth cues. These techniques were used for visible or occluded virtual data.

6.2.1 *Geometrical Depth Cues*

Predefined virtual geometries, such as virtual ground planes or parallel lines, support the depth comprehension by providing additional depth cues (Figure 10). Usually, these additional cues are available in a predefined geometric representation. For instance, Livingston et al. included a set of parallel lines (called tram lines) into their visualization of colored makers to improve the depth perception in an indoor and outdoor scenario [35]. Additionally, they added grid points to the tram lines (Figure 11, Left). The authors conducted a user study investigating this visualization technique and confirmed on a positive effect for depth estimation outdoors. It seemed that the users were tending to decrease overestimated depth judgments in outdoor environments. For indoor usage adding the tram lines was counterproductive, since it decreased the already underestimated depth.

Livingston et al. also introduced other examples of using external geometries to improve the depth perception in AR. For instance, they implemented a ground grid visualizing a virtual plane on the ground that either shows the distance to the user with concentric circles or with parallel lines [66]. Their graphical aid restore the visual cues of height in visual field, and relative size. The ground plane geometry can be

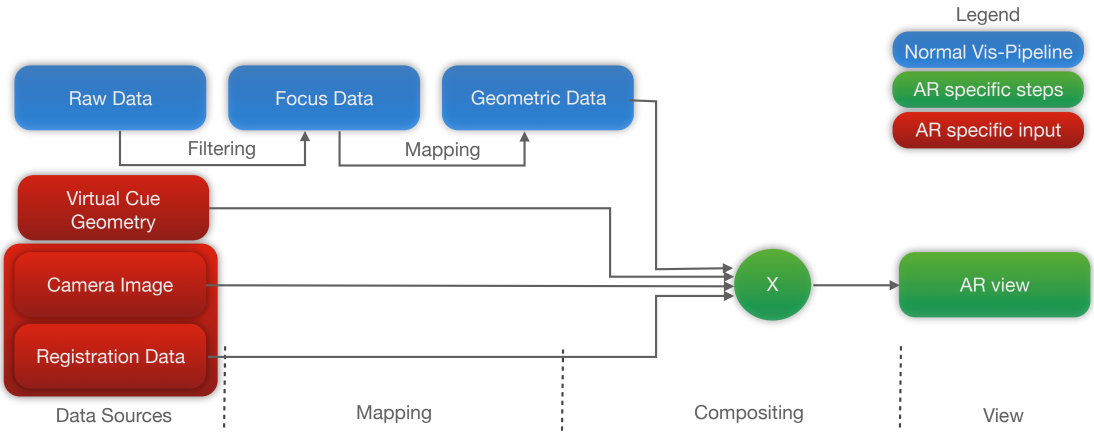

Fig. 10: Pipeline for creating external virtual cues. An external geometry is added to the compositing step in order to create additional depth cues. The camera image is only needed for video see-through displays or when extracting other image features.

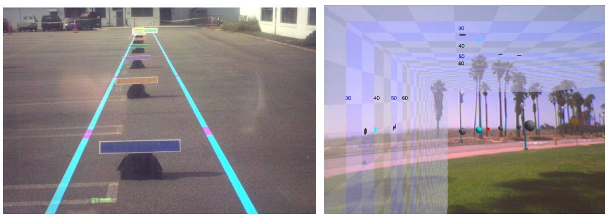

Fig. 11: Examples for using external virtual cues. Left) Adding a set of parallel lines to improve the depth perception (Image courtesy of the U. S. Naval Research Laboratory, Livingston et al. [35] ©[2009] IEEE)). Right) Virtual Shadow Planes for visualizing absolute depths (Wither et al. [63] ©[2005] IEEE).

extended by ties that show the connection between the virtual object of interest and the ground plane. This feature is in particular interesting for floating or subsurface objects, since it shows the connection between these objects and the ground. Wither et al. introduced a similar concept with the *Shadow Planes* [63]. The shadow planes consist of two orthogonal planes with depth measurements that are used to project shadows of virtual objects onto it (Figure 11, Right). The shadows in combination with a virtual distance scale on the planes was introduced to support the user in judging distances. Nevertheless, first study results showed no significant improvement using this technique.

6.2.2 Appearance Cues

Less obstructive, but also less direct are methods that encode the distance into the visual appearance. These methods form the second group of virtual cues. In Figure 12, we show an instance of the AR visualization pipeline that reflects this mapping. The pipeline adds the distance from the user to the virtual object to the mapping process and includes it into the visual appearance of the object. Thereby, the registration data helps to compute the distance between virtual object and user. Visual characteristics that are used to encode distance are transparency, color, frequency of stipples or density of virtual edges.

This kind of mapping was discussed by Livingston et al. [112]. In their work, the authors suggested to change opacity and intensity of building renderings based on their distance. They compared this visual mapping to constant opacity and constant intensity and found a significant effect of using decreasing opacity on depth estimation (Figure 13. Left). Uratani et al. discussed how to map monocular depth cues to the appearance by using the distance of labels such as [62]:

- Depth of field by blurring the frame of the label depending on the distance.
- Relative size by changing the size of the label's frame.
- Aerial perspective by changing the saturation of the label as a function of distance.
- Texture gradient by including a texture pattern into the label.

In their final implementation they encoded the absolute distance into a color pattern (Figure 13, Right). More recently, Livingston et al. used a set of mapping techniques to encode depth of virtual targets and compared them to each other [66]. Mappings that they used to encode the distance comprise:

- Stipples around the target, whereby the frequency increases with the distance.
- Opacity of the target that decreases with the distance.
- Synthetic edges around the target, whereby the distance is encoded in the spatial frequency of the edge pattern.
- Tunnel metaphor that uses squares around the target, whereby the number of squares depends on the number of occluding layers to the user (Figure 13, Right).

In a user study with professional users from the

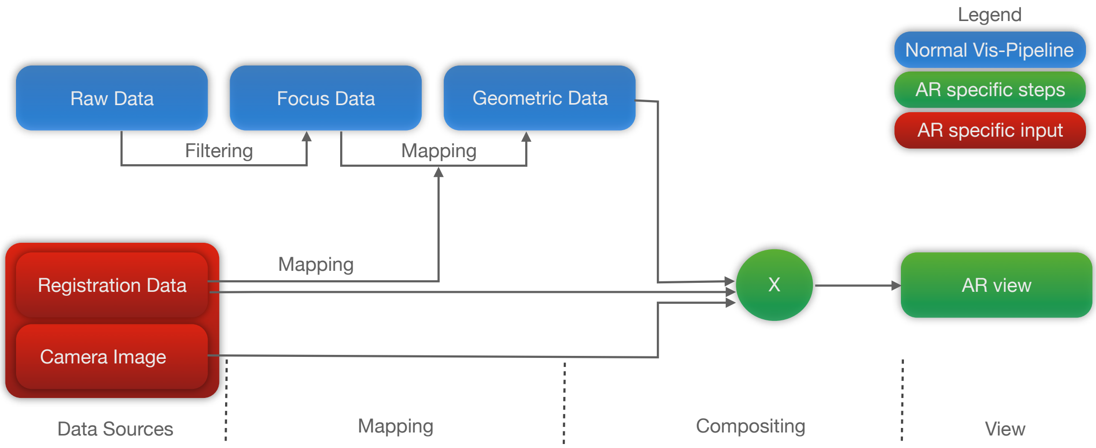

Fig. 12: Pipeline for mapping distance to appearance. The camera image is only needed for video see-through displays or when extracting other image features.

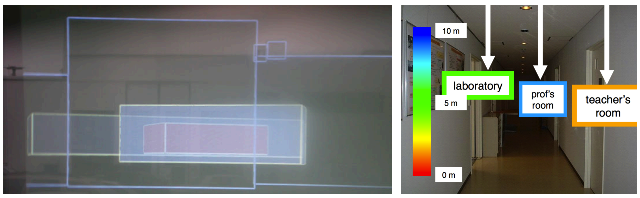

Fig. 13: Mapping from distance to appearance. Left) Using intensity and opacity for encoding depth (image courtesy of the U. S. Naval Research Laboratory, Livingston et al. [112] ©[2003] IEEE). Right) Using color to encode distance (Uratani et al. [62], ©[2005] IEEE).

military, Livingston et al. compared the cues by asking the participants to map the virtual targets to five depth zones. The results of the study showed the Tunnel metaphor to be the most helpful cue.

Another more recent work, investigated how random dot patterns can be used to generate virtual depth cues to support depth understanding in a stereoscopic AR setting [99].

While the mapping metaphors can provide absolute or relative depth measurements, they are usually not so well designed for maintaining visual coherence. In the next paragraph, we will show virtual cues aim support both.

A special type of virtual depth cues are cutaways. Cutaways are visualization techniques that focus on supporting depth perception for occluded data. For this purpose, a part of the occluding object is cut out and reveals the hidden content. Cutaways are often considered as being part of the group of Focus&Context techniques, since they allow one to inspect data in the cutaway area more in detail. But actually they can do more than filtering. They are also able to provide virtual depths cues, such as a box around the hidden object that shows measurements or perspective cues given by the shape of the cutout geometry. In contrast to using external geometries or mapping distance to appearance, the creation of cutaways requires extensive information about the physical world. Similar to the ghosting techniques, cutaways have their origin in illustrations and technical drawings, where the artist wants to reveal hidden parts of an object to the observer.

The input that is required to create a convincing cutaway in AR comprises a cutout geometry as well as a model of the occluding object. Since the occluding object is in this case the physical world, we need contextual data about the physical world (Figure 14). This data could be a rough surface model or a phantom geometry. By combining the cutout geometry and the phantom model, we can compute the correct cutout by aligning the cutout to the surface of the physical world object.

In their research from 2002, Furmanski et al. discussed general guidelines for designing X-Ray AR systems [59]. Among different suggestions for visual aids (ground planes grids, distance marker and temporal distance markers), they showed how to render virtual cutaways on a wall to reveal hidden information. In a user study, they compared the visualization of a target inside a wall with and without cutaways. Contrary to the expectations, the study showed that the virtual cutaways do only help to understand the location of the virtual target for a dynamic video sequence, where the target was partially occluded by the frame of the cutaway box. But the authors stated that the findings from their study can be influenced by technical limitations of the AR system. This was confirmed by the participants reporting that their perception was influenced by the jitter from the registration.

Later on, Kalkofen used cutaways to visualize the interior of a miniature car. They used a phantom representation of the occluding object (the car) to compute the bending of the contour of the cut-out area. Based on this information, they were able to preserve the shape of the occluding object [47]. Fur-

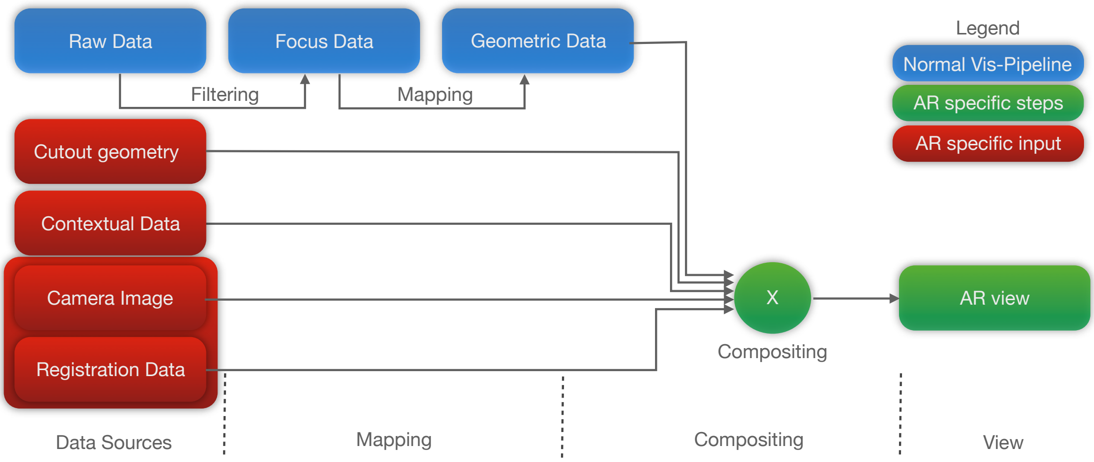

Fig. 14: Creating additional virtual cues with cutaway geometries. The camera image is only needed for video see-through displays or when extracting other image features.

Fig. 15: Cutaways as virtual cues in AR. A virtual excavation with a depth scale is used to visualize subsurface infrastructure (Zollmann et al. [113]).

ther, the work of Kalkofen showed that the cutout is not enough to transfer the depth of a detached hidden object. In this case, the visualization technique should provide additional hidden aids or geometries. Kalkofen, addressed this by rendering the cutout volume to add depth cues.

Mendez et al. showed how to include such additional visual hints in a cutaway visualization [114]. They rendered a virtual excavation with depth measurements to visualize subsurface infrastructure in an urban civil engineering scenario. The virtual box allows the user to estimate the depth of the hidden objects. Furthermore, occlusions between the virtual pipes and the textured box allow to support the depth perception, since it shows the exact spatial relationship between the cutout geometry and an object of interest.

This method was automatized by Zollmann et al. with a dynamically configurable transcoding method that allows for generating cutaway geometries automatically from GIS data [113] (Figure 15).

6.3 Filtering Pipeline

The main goal of information filtering is to reduce the complexity by decreasing the amount of displayed information based on a defined logic. In AR, location, user objectives and user-defined focus areas were used to control the filtering (Figure 16). One of the early research works that investigated filtering in AR is the work of Julier et al. [72]. They proposed a system for reducing information clutter in a mobile AR system by calculating a focus and nimbus area based on the user's location and objectives. Based on this information, they calculated the importance of virtual buildings and used it to decide whether a virtual building should be culled or not. A fading function provides smooth transitions between filtering levels to avoid that small changes in user's positions extremely change the displayed content. Later, Livingston et al. used a similar filtering approach based on focus and nimbus areas of objects of interests for removing clutter in military AR operations [66].

Focus&Context techniques in AR allow to filter virtual information based on an interactively defined spatial logic. For instance, Looser et al. introduced an interactive magic lens for defining a focus area [115]. Users of their system can control the lens with a physical marker. Based on this selection, only the area inside the lens displays virtual data. This allows the user to inspect the virtual data while avoiding a cluttered context area. Additionally, the filtering criteria of their magic lens tool can be configured during run-time. Other interactive Focus&Context tool are the interactive X-Ray tunnel and the room-selector tool from Bane and Höllerer [74]. These tools allow defining a focus area that display virtual data, such as heat distribution of a building (Figure 17, Left). Kalkofen et al. used Focus&Context filters in a scene graph to allow users to explore occluded information in an X-Ray view (Figure 17, Right) [29].

6.4 Data Transformation Pipeline

The drawback of filtering techniques is that they eliminate information to avoid information clutter. In contrast, transformation techniques do not completely remove non-relevant information, but trans-

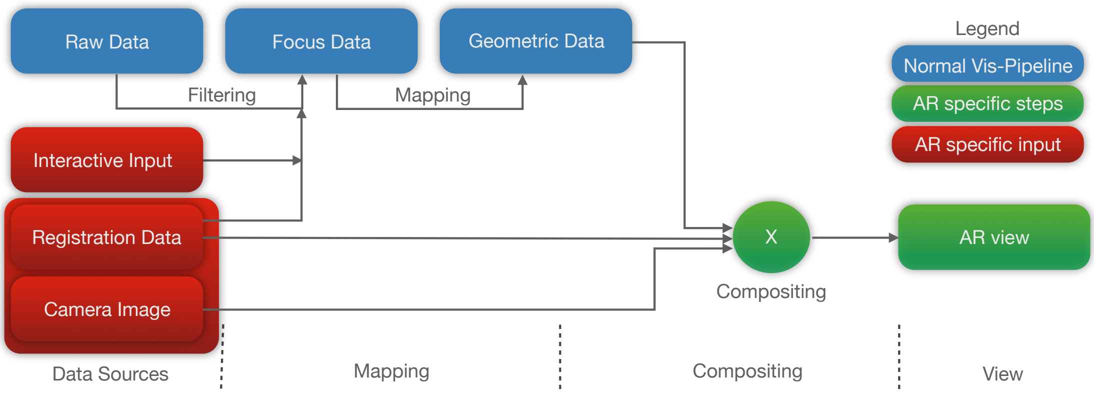

Fig. 16: Information filtering pipeline. The camera image is only needed for video see-through displays or when extracting other image features.

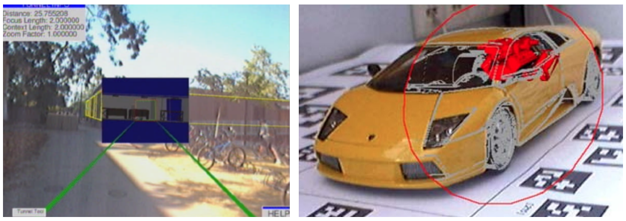

Fig. 17: Filtering pipeline examples using Focus&Context techniques for information filtering in AR. Left) Interactive X-Ray tunnel (Bane et al. [74], ©[2004] IEEE). Right) Focus&Context tools allow to explore occluded information in an X-Ray view (Kalkofen et al. [29] ©[2007] IEEE).

form it. Transformation techniques were developed in the context of information visualization, but were also already applied for AR visualizations. In AR, either the physical world information or the virtual information is transformed to create a more clean visualization. For instance, inspired by illustrative techniques Kalkofen et al. created explosion views to remove occluding areas from a hidden object of interest [77]. Their technique translates occluding parts to a new position to reveal occluded information. Recently, Tatzgern et al. extended these techniques by using compact explosion views to avoid that transformed content infers with the environment [78].

Other examples for transformation techniques are distortions. Distortion methods have been used in information visualization and interface design [116]. Those methods aim to reduce the space used up for the visualization of non-relevant information by distorting it allowing to keep non-relevant information available for a fast overview. Sandor et al. used a distortion of occluding physical world objects to reveal occluded objects [117].

While the previous transformation methods manipulate the appearance of the physical world, approaches that focus on view management for label placement often move the actual labels in a way that all information is readable. While the techniques of Bell et al. and Azuma et al. manipulate the label placement based on the label characteristics or the relationship between labels [73], [118], the techniques by Rosten et al. and Grasset et al. apply transformation to virtual annotations in order to rearrange them based on an analysis of the current environment [119], [81].

Another option is to transform the appearance. For instance, ElSayed et al. [95] used colors and dimensions of 3D models to represent certain intensity of an ingredient in a food product.

7 Conclusion

In this paper, we analysed and classified related work in the field of visualization for AR. We described how the visualization techniques support different purpose in AR applications. With our classification, we were able to group similar techniques and to identify common design streams and pipelines. We also discussed how AR visualization techniques span through their primary purpose, the visibility of data, the depth cues used, filtering or abstraction of data and lastly the compositing methods.

When investigating the different visualization pipelines for AR, it became clear that contextual information about the physical environment is often required. This is in particular a challenge for outdoor usage or large scale environments, such as sport events. A lot of existing visualization methods in AR focus on indoor usage or small work spaces, which usually have predictable lighting and rely on a familiar environment of the physical world. Several methods even assume that a complete model of the physical world is available, which is a difficult feat for outdoor environments due to the sheer size and dynamic variables outdoors.

We also found that visual coherence seems to be the most commonly addressed aim of the investigated AR visualization techniques. Depth and occlusion cues are vital components to achieve visual coherence in AR applications. In particular X-Ray visualizations highly benefit from the integration of depth cues. Existing methods often focus either on extracting occlusion cues from a camera image or are extracting such cues from a 3D model, but therefore relying on accurately modelled environment. Combining both, image-based cues and model-based cues seems to be a promising area that is still under-explored.

While support for depth perception, reducing information clutter and exploration are similarly popular purposes for AR visualization techniques, attention direction has only been explored in a smaller number of research works and has potential for further investigations. In particular here, aspects of how to use virtual and physical perceptual cues could be used for guiding attention could be interesting to investigate further.

Finally, we should state again that we focus on general visualization issues in AR. As pointed out earlier, specific AR displays might require additional steps specific to this display to achieve some of the goals outlined in this work. In particular optical see-through displays pose their own challenges as they do not give full control over the environment as assumed in this work and possible with video see-through AR (e.g. rendering correct occlusions is challenging with current hardware as it is only possible to add light [7]).

8 Future Work

In the context of creating a taxonomy and reviewing related work in AR, there are still unexplored fields in AR that are not included in this paper. Applications with huge databases might need a more complex and automated way to visualize virtual cues to support depth perception. Complex multidimensional data in AR is also a field which is still not properly investigated. What are the visualization methods to visualize 4D representations where users could understand the relationship between the multiple datasets? Also the Internet of Things (IoT) is definitely one of the most promising future application areas for AR that could benefit from research in visualisation techniques in AR. IoT devices are embedded in our environment and besides a mobile app they often do not show the captured information. AR and in particular sophisticated visualisation techniques could provide an intuitive interface to the large amount of rich data used by the IoT. This trend is among other discussed by Norouzi et al. [120] but they envision an intelligent virtual agent representing the data while visualisation techniques as presented in this paper could make the raw data more accessible.

As for future AR research itself, we hope our AR visualization pipelines and taxonomy contribute to any future AR applications. We highlighted on how visualization techniques currently are often limited to indoor usage. Considerably, more work needs to be done in order to achieve a robust AR system that could function well indoors and outdoors while providing visual coherent visualizations.

Acknowledgments

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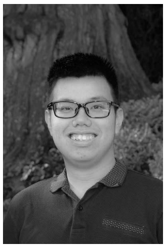

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