

# Towards Pervasive Augmented Reality: Context-Awareness in Augmented Reality

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**Abstract**—Augmented Reality is a technique that enables users to interact with their physical environment through the overlay of digital information. While being researched for decades, more recently, Augmented Reality moved out of the research labs and into the field. While most of the applications are used sporadically and for one particular task only, current and future scenarios will provide a continuous and multi-purpose user experience. Therefore, in this paper, we present the concept of Pervasive Augmented Reality, aiming to provide such an experience by sensing the user's current context and adapting the AR system based on the changing requirements and constraints. We present a taxonomy for Pervasive Augmented Reality and context-aware Augmented Reality, which classifies context sources and context targets relevant for implementing such a context-aware, continuous Augmented Reality experience. We further summarize existing approaches that contribute towards Pervasive Augmented Reality. Based our taxonomy and survey, we identify challenges for future research directions in Pervasive Augmented Reality.

**Index Terms**—Augmented Reality, Pervasive Augmented Reality, Context-Awareness, Adaptivity, Context, Taxonomy, Survey, Mixed Reality.

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## 1 INTRODUCTION

THE rise of mobile and wearable devices, the increasing availability of geo-referenced and user generated data and the accessibility of high speed, mobile networks spurs the need for user interfaces, which provide the right information at the right moment and at the right place. Augmented Reality (AR) is a user interface metaphor, which allows for interweaving digital data with physical spaces [1]. AR evolves around the concept of overlaying digital data onto the physical world, typically in form of graphical augmentations. These augmentations are spatially registered in three-dimensional (3D) space and are interactive in real-time [2]. This enables the users of AR systems to interact with their physical and virtual environments instantaneously.

Over the last years, AR started to move out of lab environments into the field. In particular, several companies have started to roll-out AR applications to consumers, which are downloaded by millions of users and used in a multitude of mobile contexts [3], [4]. For example AR Browsers, applications to access Internet information that is registered to places or objects using an AR view, are used for navigation in indoor and outdoor environments by augmenting routing information, for marketing purposes by augmenting interactive 3D media on magazines, posters or products, for mobile games by augmenting interactive virtual characters registered to the physical world, or for ex-

ploring the environment as part of city guides (e.g., retrieving Wikipedia information augmented into the users' view) [5]. Figure 1 shows some examples for AR applications such as stroke rehabilitation, design review or city guides using textual augmentations.

Despite the recent success of AR applications, these applications serve usually a single purpose and are used only for short times. Standard AR hard- and software solutions prevent a continuous, multi-purpose usage of the interface. However, recent developments of head-mounted hardware or car-integrated head-up displays are enablers for a continuous AR experience, providing potential always-on access to information [8], and with this for a more versatile information integration in everyday scenarios. We call this continuous AR experience *Pervasive Augmented Reality* as an continuous, omnipresent, and universal augmented interface to information in the physical world. The concept of Pervasive Augmented Reality requires that the AR system can adapt to the current, changing requirements and constraints of the user's context and thus allows for a continuous usage. Extending Azuma's definition of Augmented Reality [2], we define Pervasive Augmented Reality as a continuous and pervasive user interface that augments the physical world with digital information registered in 3D while being aware of and responsive to the user's context.

In general terms, context can be seen as being "any information used to characterize the situation of an entity. An entity is a person, place or object that is considered relevant to the interaction between a user and an application, including the user and the application themselves". Similarly, context-awareness is defined as "the facility to establish context" [9]. Given the nature and definition of AR, location has been handled as the major context source, but there is a multitude of other context factors that have an impact on the interaction with an AR system, for instance a host of human factors. In this article, we investigate the

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Fig. 1. Examples for traditional, non-continuous Augmented Reality applications. (Left) Augmented Reality in a stationary, monitor-based setup (here for stroke rehabilitation) [6], (Middle) Augmented Reality with head-mounted displays (here a collaborative design review scenario) [7], (Right) Augmented Reality on mobile devices (here spatially aligned outdoor information) [5].

concept of Pervasive Augmented Reality and the different contexts it can be aware of to support a continuous usage.

As AR is increasingly used in real-world scenarios, there is a need to better understand the specifics of AR interfaces in different contexts beyond location-awareness, impacting on visualization and interaction techniques for AR applications. Traditional AR applications are typically used for short periods of time and for specific purposes. Figure 1 presents three examples. First, in a stationary, desktop-based system setup the user's hands are merged with a virtual environment to confuse patients in stroke rehabilitation about ownership and movements of their hands [6]. The system uses customized off-the-shelf hardware for a specific therapeutic purpose and only for the duration of the rehabilitation session. The second AR example allows multiple users wearing video see-through head-mounted displays to view and discuss computer aided design models on a table [7]. The system uses networked, standard computers, modified virtual reality head-mounted displays and the software is tailor-made for this design review scenario. The last example in figure 1 demonstrates a common traditional AR scenario: A mobile phone's back facing camera is used to implement an AR video see-through mode and to overlay textual information about the surrounding environment. The text elements are spatially registered and aligned with objects (buildings) in the real world [5].

Some applications allow for a context-aware experience of overlaid information, even if purpose-built and not intended to be used continuously over very long periods of time. In particular information overlay in vehicles is aiming in that direction. Figure 2 shows two scenarios. First, modern fighter aircrafts are equipped with head-up displays which are constantly in the pilot's view [10]. The information is presented in a way that allows for the least distraction and for most relevant, up-to-date information depending on the current location and context of the airplane. The second example shows a co-operative driver training scenario, where both the trainer and the driver wear video see-through head-mounted displays [7]. Now, in the driver's (and trainer's) view, situations can be presented depending on the location, but also on the current vehicle information, e.g., speed, steering wheel angle, accelerometer data, or breaking characteristics.

While all those applications are of relevance and value for users, they do not allow for a continuous, universal,

context-aware AR experience. These applications and systems are just beginning to emerge, mainly driven by advances in consumer-oriented hardware developments like Google Glass, Microsoft HoloLens, or Meta Augmented Reality Glasses. To date, those systems are typically offered to developers, but are about to be released to the general public soon. The question emerges then, on how those systems would implement a pervasive AR experience. Of particular interest here is the aspect of the continuous and context-aware use. Figure 3 illustrates the concept of Pervasive Augmented Reality. The user is using an AR interface within different contexts such as a work environment (sitting at a desk), a outdoor environment such as navigating through cities, or in a meeting context with other participants using a AR interface. For each scenario the user is provided with varying forms of AR information overlay. Depending on the user's current context and goals the environment changes in its information presentation. Not only the change in location and viewing direction, e.g. being indoors or outdoors, but also the sequence of interactions, e.g., hand gestures in private spaces vs. unobtrusive interactions in public spaces as well as the availability of suitable interactive devices and surfaces, e.g., semantically classified objects like the desktop, are determining what information content and how this content is displayed. With as little as possible required direct user interaction the augmented environment information adapts to the current context of use. The user is continuously experiencing the environment in an adaptive way. This is the kind of experience we are targeting with our research.

Overall, our work brings together research from different fields related to this topic (e.g., Augmented Reality, Pervasive Computing, Human-Computer Interaction, or Intelligent User Interfaces) and contributes to the body of knowledge by a) presenting the concept of Pervasive Augmented Reality as a continuous AR experience based on context-awareness, b) developing a taxonomy for Pervasive Augmented Reality and the context factors involved, c) providing a comprehensive overview of existing AR systems towards our concept and vision of Pervasive Augmented Reality and how they adapt to varying contexts, and d) by identifying opportunities for future research to implement Pervasive Augmented Reality.



Fig. 2. Examples for context-aware information overlay applications (Left) A head-up display in the pilot's view in a fighter airplane [10], (Middle and Right) Driver and trainer in an AR-based driver training setup and a virtual car and child embedded into the driver's view [7].

## 2 BACKGROUND

Pervasive Augmented Reality combines concepts from Augmented Reality with concepts context-aware computing. In the following, we give an introduction to both fields.

### 2.1 Augmented Reality

AR encompasses user interfaces that allow for interaction with digital content embedded into the physical environment of users. For this purpose, AR interfaces superimpose digital information, such as 2D or 3D graphics on the user's view of the physical environment in real-time. Azuma defined the main characteristics of AR interfaces as 1) the combination of virtual and physical elements, 2) being interactive in real-time and 3) being registered in 3D [2]. First implementations appeared in the 1960s with Ivan Sutherland's "The sword of Damocles" [11], first industrial applications with and head-mounted display in the 1990s [12] as well as with handheld displays (e.g., [13], [14]). Today, mobile AR applications are used among others for browsing situated media with AR browsers [5], museums guides [15], mobile gaming [16], navigation tasks [17], product marketing as well as for industrial applications [18].

AR applications usually comprise three components: A tracking component, a rendering component, and an interaction component. All of these components can be considered as essential. The tracking component determines the device or user position in six degrees of freedom (DoF), which is required for visual registration of the digital content and its physical surroundings. Based on tracking data the scene (e.g., 3D models and camera images representing the physical world) is composed in the rendering component. Finally, the interaction component allows the user to interact with the physical and digital information.

A wide variety of motion tracking approaches has been employed in AR, including magnetic, mechanical, inertial, ultrasound, GPS tracking [19], [20], and to a large extend vision-based tracking [21] ranging from visible marker detection [22] and natural feature tracking [23] to 3D-structure tracking (e.g., [24], [25], [26]).

Displays for AR typically encompass video see-through (head-mounted, stationary, handheld or wearable), optical see-through (e.g., [27], [28], or projection-based systems (e.g., [29], [30], [31]) or a combination of those (e.g., [32], [33], [34]) or to a lesser extent other sensory displays

(e.g., haptic [35] or olfactory and gustatory displays [36]). Rendering challenges for AR encompass, amongst others, photometric registration [37], [38], comprehensive visualization techniques (e.g., [39], [40], [41]), or view-management techniques (e.g., [42], [43]).

Interaction techniques for AR encompass traditional 3D user interface techniques [44], tangible user interfaces [45], [46], natural user interfaces (e.g., [28], [47], [48], and multi-modal interaction (e.g., [45], [49], [50]).

One of the differentiation factors in AR systems is the mobility aspect. Hence, existing AR systems can broadly be divided into stationary/desktop AR systems and mobile AR systems. The first category can be of particular interest for professional applications (e.g., in the medical domain) or console-based gaming where the user has some degree of freedom but is usually bound to a stationary computing unit. In contrast, mobile AR systems rely on mobile personal displays. While we would envisage that the majority of Pervasive Augmented Reality systems would be utilizing devices around the human body (e.g. mobile, wearable, wrist-worn, head-worn) a context-aware and continuous experience can also be achieved by incorporating stationary PAR systems. This can either be a simultaneous use of mobile PAR systems, akin to Grubert's MultiFi concept [34] or by switching from one device to another with only little interruption of the continuity of the experience. The recent availability of affordable head-mounted displays (HMDs) like Google Glass and the availability of smartwatches like the Apple Watch will likely shape how users interact with AR applications in the future, providing potential always-on access to information [8].

There is a variety of surveys on AR that give an appropriate overview of the field (e.g., [51], [52], [53], [54], [55], [56], [57], [58]). Those survey papers address different AR aspects ranging from general overviews of the field to specialized topics such as user-based experimentation. In contrast to general AR surveys, we specifically focus on how context-awareness has been considered in AR systems so far. Based on this state of the art review, we propose next steps to achieve pervasive AR.

### 2.2 Context-Awareness

Context and context-awareness have been thoroughly investigated in various domains such as ubiquitous computing,



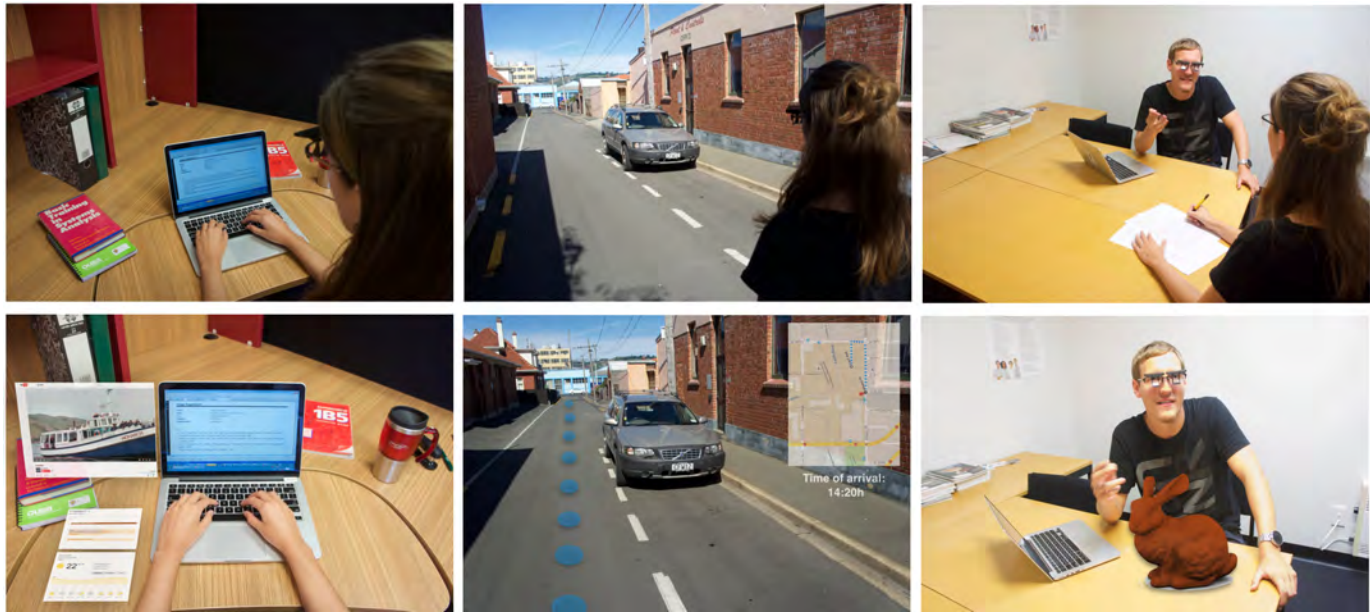


Fig. 3. Examples for the concept of Pervasive Augmented Reality requiring a device to accommodate to different scenarios: (left) Using PAR to extend the physical screen with overlaid widgets. Being adaptive to the environment allows to use model-based tracking to track the known environment (office) and allowing hand-based interaction with the system. (middle) Using PAR in outdoor environment providing navigation cues. The system must sense the context such as location but also analyse the environment adapting the system to only have minimal overlays not occluding important features (approaching cars) while also allowing for a social acceptable interaction with the system (e.g., touch interaction with the devices, eye-tracking). Tracking is application dependent and can vary between sensors only or vision-based. (right) PAR in a meeting scenario supporting meeting participants by giving access to shared virtual objects or documents which are perspectively correctly overlaid for all participants requiring a synced virtual space. This scenario requires the ability to adapt the system based on the proximity of other known users using a PAR system and their location.

intelligent user interfaces or recommender systems. Theoretical foundations about the semantics of context have been discussed in previous work e.g., [59]. Different taxonomies and design frameworks e.g., [60], [61] as well as numerous software-engineering centric models for context and contextual reasoning have been proposed by other research groups, e.g., [62]. In addition, comprehensive reviews of context-aware systems and models were published e.g., [63], [64], [65], [66]. Finally, there have been discussions if capturing context in a general sense is of any use to inform the design (and operation) of mobile and ubiquitous systems as it is tightly bound to (hardly accessible) users' internal states and the social context [67], [68]. We argue that it is worthwhile to make these various context sources explicit, even though we might not have the means to measure all possible sources, yet (such as users' cognitive state). Within this paper we follow the generic notion of context by Dey et al. as "any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves" [9]. Similar to discussions about several context aspects, diverse taxonomies and design frameworks to capture context factors have been proposed. While philosophical aspects of context have been discussed [59], [69], the majority of existing works deal with technology oriented approaches. For example, in the domain of pervasive systems, Abowd et al. introduced the primary context factors of location, identity, activity and time to address the questions of where?, who?, what?, and when? [9]. The authors also proposed to model secondary context factors, i.e. factors

that are subcategories of primary factors (e.g., the e-mail address as subcategory of what), which could be indexed by the primary factors. Schmidt et al. proposed a working model for context with the two primary factors physical environment and human factors [70]. They express several cascaded factors and features within these two primary factors. Examples include user habits and affective state, users' tasks, co-location of other users and interaction with them for human factors. The physical environment includes location, infrastructure and physical conditions (e.g., noise, light, pressure). They also suggest considering the history of the context itself as relevant feature.

Hong et al. propose a categorization into preliminary context (raw sensor measurements) integrated context (inferred information, specifically from sensor fusion), and final context (information processed by the application, trying to encompass higher level reasoning about users' intentions). On a meta level, according to Hong et al., context can be divided into primary, integrated and final context [71]. Preliminary context considers raw measured data. Integrated context contains accumulated preliminary contexts and inferred information. Final context is the context representation received from and sent to applications. For example, a raw measurement could be provided by a linear accelerometer of a mobile device, which is combined with other sensor measurements of gyroscopes and magnetometers to deliver an integrated rotation measurement. Combined with location data and the audio level measured the system could infer a "meeting situation" and automatically mute the mobile phone. This three-level categorization follows models about human perception, which assume a

multi-layered perception pipeline e.g., for human vision divided into early, intermediate and high-level vision [72].

Thevenin and Coutaz introduced the term “plasticity”. According to them plasticity “is the capacity of a user interface to withstand variations of both the system physical characteristics and the environment while preserving its usability” [73]. Hence, it can be seen as a focus of context-awareness on the system level. They identified four dimensions for adaptation: target, means, time, actor. The target for adaption are “the entities for which adaptation is intended: adaptation to users, adaptation to the environment, and adaptation to the physical, characteristics of the system”. Means of adaptation are the “software components of the system involved in adaptation”, e.g. the system task model or rendering techniques. The authors differentiate the temporal dimension in static and dynamic components. Actors can be the user or the system. Lacoche et al. used a different categorization for plasticity [74]. Specifically, they differentiated between adaptation targets (content, interaction techniques), sources (hardware, users, semantic), controller (user, system) and time (runtime, compile time). While plasticity concentrates on keeping a system usable in varying usage scenarios, context-aware systems might also offer new services or functionalities depending on the user’s situation.

Context-aware recommender systems generate relevant recommendations for users based on the contextual situation of users [75], [76]. In fact, context-aware AR user interfaces can be seen as an instance of recommender systems, as they present adapted content to users, based on their specific situation.

There is also a considerable body of work which concentrates on the modeling of context for pervasive systems (see e.g., [64], [65]) and for AR [77], [78], [79].

The presented approaches use general notions of context factors, which allow them to address the problem space of context-awareness on a big scale. It is noteworthy, that most taxonomies agree on those top-level factors (human factors, technological factors, environmental factors, temporal factor). However, we believe that extending those top-level factors with further secondary and tertiary context factors can ease informing the design of interactive systems. Specifically, for the domain of AR, which by its nature combines attributes of the physical environment and digital information, a comprehensive overview of how context-awareness is addressed and which context factors are relevant for interaction is missing to date. We highlight the fact that by their nature AR interfaces are context-aware as they use localization information with 6 DoF to integrate digital information into their physical surrounding. Hence, for this article we concentrate on research that investigated context factors other than spatial location.

### 3 PERSVASIVE AUGMENTED REALITY: DEFINITION AND TAXONOMY

In the foreseeable future, Pervasive Augmented Reality might develop into a disruptive user experience concept the same way as personal computing or mobile communication with cell phones significantly changed the way we work or interact. The move from mainframe computers to

personal computers turned computers from task-specific, batch-processing “number crunchers” into universal, always accessible working devices. The move from landline telephones to mobile smart phones turned specialized voice communication devices to be accessed and operated in one room of the house into ubiquitous, always-at-hand communication and information devices. Now, the move from Augmented Reality to Pervasive Augmented Reality aims to turn spatial information overlay for specific purposes into an always-accessible, universal information and communication interface. Recent advances in the development of AR capable hardware, like pervasive and wearable computing devices and infrastructures, as well as novel possibilities in using advanced software developments, like sensor fusion, prediction, and analytics are enablers for Pervasive AR user experiences. Nowadays, we see consumer-oriented hardware that is specifically designed to operate an AR interface. This includes head-mounted displays with integrated processing units such as Epson’s optical see-through head mounted displays, Microsoft’s HoloLens but also head-up displays integrated into cars. In contrast to early head-mounted displays targeted at single purpose use cases in industrial [12] or military domains, the current generation of head-mounted displays target multi-purpose use in a variety of usage contexts. Here, AR can be the key and main interface and using the hardware would literally mean using an AR interface. Now, those interfaces have the potential to be used continuously, almost all the time and not, like with the use of personal computers or smartphones being turned on or called upon. A key differentiating factor between head-mounted displays and smartphones is the lower access cost to information of head-mounted displays and other wearable displays. Smartphones have a comparable high access cost due to the need to retrieve and store away the devices in the user’s pocket, resulting in fragmented information access in short bursts [80], [81].

Continuous AR experiences raise challenges about appropriate information display and interaction, which is unobtrusive, not distracting, and is relevant and safe to use. A new class of user experiences around the right, yet disappearing interface develops - here our concept of Pervasive Augmented Reality becomes relevant.

#### 3.1 Pervasive Augmented Reality

Pervasive Augmented Reality is a continuous and pervasive user interface that augments the physical world with digital information registered in 3D, while being aware of and responsive to the users context. Hence, Pervasive Augmented Reality can be seen as a context-aware and responsive, continuous Augmented Reality experience. This differs to conventional Augmented Reality but also to previously introduced concepts such as Context Aware Mobile Augmented Reality (CAMAR) [71]. CAMAR can be seen as a subgroup of the PAR concept since it focuses only on the personalization aspects for mobile AR while PAR focuses on other context sources than only the user of the system. Table 1 summarizes differences between conventional Augmented Reality and Pervasive Augmented Reality (PAR).

The main difference between PAR and conventional AR is the temporal component of the use. Conventional

AR systems are used rather sporadically, ad-hoc and not in a continuous mode like PAR systems. To date, an AR application is turned on or activated, used and turned off or deactivated again. This becomes apparent when looking at mobile phone based AR applications in video see-through mode: Users are holding the phone in front of their eyes like a compact camera to get the augmented experience. If not for other reasons, even holding the phone for longer periods would lead to fatigue (the "Gorilla arm effect") and prevents continuous use.

PAR systems are mainly controlled by the user's current context factors and to a lesser extent by direct user control. In an AR system users switch between different tasks and views, like changing from traffic information views to entertainment functions. In PAR systems with their constant information augmentation this would lead to a much too frequent need to interact with the system. Provocatively speaking, the user would have to entertain the PAR system all the time. While not all system control can practically be done by context factors only those user control activities should be kept to a minimum.

Conventional AR applications are built for particular tasks and purposes, e.g. navigation information provision or 3D model visualization in a real-world context. Therefore, different AR applications exist for a plethora of different purposes. With PAR, the PAR system itself defines the interface and serves multiple, if not all purposes of use. E.g., navigation information is delivered through the same PAR interface as 3D model visualization. The same is true for the context of use. To date, AR applications are designed to be used in a restricted, specific context while PAR applications must work in all contexts and be adaptive and context aware.

Current AR applications are designed with general purpose hardware as targets. For instance, mobile AR applications are executed on smart phones, stationary applications like the Augmented Reflection Technology system [6] are using standard personal computers and monitors, and even head-mounted display based AR applications are using standard virtual reality gear, though modified, e.g. with a camera. PAR systems will and do already use tailored hardware. For instance, Microsoft's HoloLens system is designed for a continuous AR experience.

We might even dare to state, that only PAR delivers a true augmented reality experience by moving away from simple information overlay, which is added to a scene towards actual information augmentation, embedding virtuality into reality. Also, mainly caused by new ways of user interface control, the continuity of use, and the context-driven nature of PAR users do not actively seek information any longer, rather information is delivered to users or "seeking users". We are moving away from a "one size fits all" AR interface to an individualized, pervasive augmentation experience.

### 3.2 Taxonomy for Pervasive Augmented Reality

Existing taxonomies from the ubiquitous computing domain captured several viewpoints, mostly technology focused, but also address phenomenological aspects. Most of them are coarse (typically only having one to two levels of context

factors), leaving the association of finer grained factors to the researchers who apply the taxonomies [70]. For the domain of PAR our goal was to identify a detailed classification of context sources, which are relevant for context-aware PAR interactions. This is mainly needed for two reasons. Firstly, because existing context-aware AR approaches often focus on one single specific context aspect instead of integrating a larger group of factors. Thus, a finer granularity makes it easier to discuss existing works on context-aware AR, which show how to partially address the vision of PAR, and sorting them into the overall taxonomy. Secondly, the finer granularity of the new taxonomy allows us to identify underexplored research areas in particular in the field of PAR.

### 3.3 Methodology

For creating the classification we combine high-level categories of previous taxonomies with bottom up generation of individual categories.

Specifically, we re-used the high level categories of context sources, context targets and context controllers proposed in previous work [74], [82]. Context sources include the context factors to which AR systems can adapt. Context targets addresses the question "what is adapted" and corresponds to the "adaptation targets" category previously proposed [74]. This domain describes which part of the AR system is the target of the adaptation to external context factors (e.g., the visualization of an AR application). Context controller deals with the question "how to adapt?" and corresponds to controller of the adaptation process in previous work [82]. It identifies how the adaptation is implemented: implicitly through the system (adaptivity) or explicitly through user input (adaptability).

Furthermore, for the category context sources we re-use high-level concepts that broadly cover general entities in human-computer interaction [83], which were also employed in taxonomies in the mobile and ubiquitous computing domains (e.g., [70]): human factors, environmental factors and system factors (see Figure 4, right).

In addition, we created individual classifications through open and axial coding steps [84]. Specifically, a group of domain experts in AR individually identified context factors relevant to AR. Those factors were partially but not exclusively based on an initial subset of the surveyed papers. Then those individually identified factors were re-assessed for their relevance to AR in group sessions. These group sessions were also used to identify relations between factors and to build clusters of factors that were integrated into the high-level concepts derived from previous work (eventually leading to the presented taxonomy). It became clear that some factors could be seen as part of several parent factors depending on the viewpoint. For example, information clutter can be seen as an environmental factor (a characteristic of the environment) but can also be treated in Human Factors (e.g., attention deficit caused by information clutter). Hence, we want to highlight the fact that, while we see the number of context factors as saturated, there are other valid hierarchical relations between the factors than the one we present here.

In the following, we will discuss these domains more in detail. In particular, we will discuss factors for which

TABLE 1  
Contrasting aspects of conventional and pervasive AR

	Conventional Augmented Reality	Pervasive Augmented Reality
Use	Sporadic	Continuous
Control	User Controlled	Context-Controlled
Applications	Specific or Niche	Multi-Purpose
Hardware	General Purpose	Tailored/Specific
Context of Use	Specific/Restricted	Multi-Purpose/Adaptive/Aware
User Interface	Prototypical/No Standard/Obtrusive	Subtle/Disappearing/Unobtrusive
Mode of Use	Task- or Goal-Oriented	Context-Driven
Information Access	Information Overlay	Information Augmentation
Information Visualization	Added	Integrated/Embedded
Environment	Indoors OR Outdoors	Indoors AND Outdoors
Flow of Information	User Seeking Information	Information Seeking Users
Use of Device	One Size Fits All	Individualized

we could identify existing publications while unexplored factors are only briefly mentioned and discussed with more details in the future directions section.

### 3.4 Context Sources

The high-level categories for context sources human factors, environmental factors and system factors together with their sub-categories are depicted in Figure 4, left and are discussed next.

#### 3.4.1 Human Factors

The human factor domain differentiates between concepts that employ personal factors and social factors as context sources. The difference between both is that personal factors are context sources focusing on an individual user, while social factors consider the interaction between several people (who are not necessarily users of the system).

**Personal factors** encompass anatomic and physiological states (including impairments and age), perceptual and cognitive [85], as well as affective states. We also separately include attitude (which can be seen as a combination of cognitive, affective and behavioral aspects) and preferences. Another context source that we identified within this sub-category is action/activity (as understood as a bodily movement involving an intention and a goal in action theory). Action/activity addresses both in-situ activity as well as past activities (accumulating to an action history).

**Social factors.** Within the category social factors, we identified two sub-categories: social networks and places. Social networks are understood as a set of people or organizations and their paired relationships [86]. Place can be understood as the semantics of a space (i.e., the meaning which has been associated to a physical location by humans). Social and cultural aspects influence how users perceive a place and one physical location (space) can have many places associated with it. Previous research has shown that place can have a major impact on users' behavior with an interactive system in general [87] and with mobile AR systems in specific [16].

#### 3.4.2 Environmental Factors

The domain of environmental factors describes the surrounding of the user and the AR system in which interaction takes place, i.e. external physical and technical factors that are not under control of the mobile AR system or the user. In

order to structure environmental factors, we took the viewpoint of perceptual and cognitive systems. In particular, we rely on the notion of "scene" which describes information that flows from the physical (or digital) environment to our perceptual system(s) in which it is grouped and interpreted.

It is important to note that the sensing and processing of scene information can be modeled on different processing layers of a system ranging from raw measurements, derived measures that rely on a priori knowledge but there is no consensus on which level certain abstractions of information actually take place. For example there are various theories about the process of human visual perception [88], [89], which are specifically popular for computer vision based analysis of the environment but differ in how they are modeled. Hence, in this paper, we solely differentiate between raw and derived measures (including inferred measures). Raw measures are provided by sensors of the mobile AR system (e.g., through a light sensor). Derived measures combine several raw measurements (e.g., gyroscope + magnetometer for rotation estimates) and potentially integrate model information to infer a situation.

Within the domain of environmental factors, we distinguish between physical factors, digital factors and infrastructure factors.

**Physical factors** describe all environmental factors related to the physical world, for instance movements of people around the user. We explicitly differentiate between raw physical factors and derived (combined) physical factors.

Raw factors include factors that can be directly perceived via human senses (such as temperature) or sensor measurement (such as time points or absolute locations in a geographic coordinate system such as WGS84). Derived factors combine several raw factors or derive higher-level factors from certain low level factors (i.e., amount of people in the environment based on recorded environment noise). One example for a derived factor is the spatial or geometric configuration. Spatial or geometric configuration of a scene describes the perceived spatial properties of individual physical artifacts (such as the extend of a poster), the relative position and orientation of physical artifacts to each other and topological properties such as connectivity, continuity and boundary. There are a number of quantitative and qualitative approaches, which try to infer human behavior in urban environments based on spatial properties (e.g., space syntax [90], or proxemics [91]).

Another environmental factor is time. We included time

as raw measure, such as a point in time, but also as derived measure (e.g. time interval as the difference between time points). It is important to note that while time may seem trivial on the first sight, it can be a highly complex dimension. Hence, more attributes of time could be of interest. For example, important attributes are temporal primitives and the structure of time [92]. Temporal primitives can be individual time points or time intervals. The time structure can be linear (as we naturally perceive time), circular (e.g., holidays such as Christmas as recurring events) or branching (allowing splitting of sequences and multiple occurrences of events).

The combination of spatial and temporal factors leads to the derived factor of presence (or absence) of physical artifacts in a scene. In particular in mobile contexts, presence is an influential factor due its high dynamic. In mobile contexts it is likely that interaction with a physical artifact can be interrupted and that artifacts become unavailable over time (e.g., an advertisement poster on a bus which stops at a public transportation stop for 60 seconds before moving on). These interruptions happen frequently [93] so AR systems should be ready to cope with them.

Other derived factors include motion of scene objects, and interpreted visual properties of a scene. Both factors could for instance be used to decide if a scene object is suitable for being augmented with digital information.

**Digital factors.** In contrast to physical factors, the second category of environmental factors focuses on the digital environment. Due to the immersive character of AR systems, several problems during the usage of AR systems are directly related to the information presented. The characteristics of digital information such as the quality and the quantity have a direct influence on the AR system. Digital information is often dependent on other context sources such as the physical environment and hence could be solely seen as a context target instead of a source. For example, the amount of Wikipedia articles accessible in a current situation can be dependent on the specific location (tourist hotspot or less frequently visited area). However, when it comes to the information presentation as it is achieved through AR, digital information can in fact be seen as a separate context source that targets the adaptation of user interface elements. Relevant attributes of digital information are type, quality, and quantity of digital information items. As an example the AR system could adapt to the quantity of available digital information by adjusting a filter as well as it could adapt to the quality of digital information (e.g., the quality/accuracy of their placement) by adapting their presentation (i.e., similar to adapting the presentation when using inaccurate sensors [94]).

Furthermore, even the results of presentation techniques themselves (e.g., clutter or legibility) have been considered as context factors. The latter factors can be seen as integrated context factors [71], which only occur due to the interaction between preliminary factors (quality of information, perceptual abilities of the user) and a processing system. It should also be noted that this processed information category is naturally connected to other categories such as the perceptual and cognitive capabilities of a user or the technical characteristics of the display (e.g., resolution or contrast of a head-mounted display).

**Infrastructure factors.** Nowadays, many AR applications are mobile applications that can work in various environments. In distributed systems, in which AR interfaces are often employed, it might be hard to draw the line between the interactive system itself and the wider technical infrastructure. At a minimum, we consider the general network infrastructure, specifically wide area network communication, as part of the technical infrastructure. For practical AR applications the reliability and bandwidth of a network connection are of high importance as digital assets are often retrieved over the network.

### 3.4.3 System Factors

Technical sources of context can concern the interactive system. As mentioned earlier we leave out infrastructure components that are used by the interactive system but are not necessarily part of the system (e.g. networks infrastructure). Factors include the general system configuration, computational capabilities of the device, output (e.g., number of displays) and input devices (e.g., touch screen vs. mouse input) connected to an AR system.

**System state.** One system factor is the interactive system itself. For instance, computational characteristics such as the platform, computational power or battery consumption can be used for adaptation as these are strongly connected to the system. In particular for AR, both sensors (such as cameras, inertial measurement units or global positioning system sensors) and their characteristics (degrees of freedom, range, accuracy, update rate, reliability) contribute to the system state.

**Output factors** describe the different varieties of presenting information to the user. Typically, systems adapt to visual output devices, such as different display types, varying resolutions, sizes or even spatial layout for multi-display environments. But output factors also include other modalities such as audio or tactile output.

**Input factors.** In contrast to output factors, input factors describe different possibilities how users can give input to the AR system. Typically, input is done via touch gestures, but it also includes gestures in general, mouse input or speech. Depending on which kinds of input modalities are available, the system could adapt its operation.

## 3.5 Context Targets

Based on the analysis of context sources the system applies changes to targets, which are parts of the interactive system [74]. Major categories that can be adapted in an AR system (and most other interactive systems) are the system input, output and the configuration of the system itself (see Figure 4, left). Standard models of HCI (e.g., [95], [96], [97]) typically differentiate between the input of a user to a computer (through input devices, modalities and techniques) and output of the computer to the user (through output devices, modalities and techniques).

For system input, the interaction modalities can be adapted. For example, the input modality of an AR system could be changed from speech input to gesture-based dependent on the ambient noise level but also based on user profiles or environments (e.g., public vs. private space).

Other approaches that adapt the input could optimize the position and appearance or type of interactive input



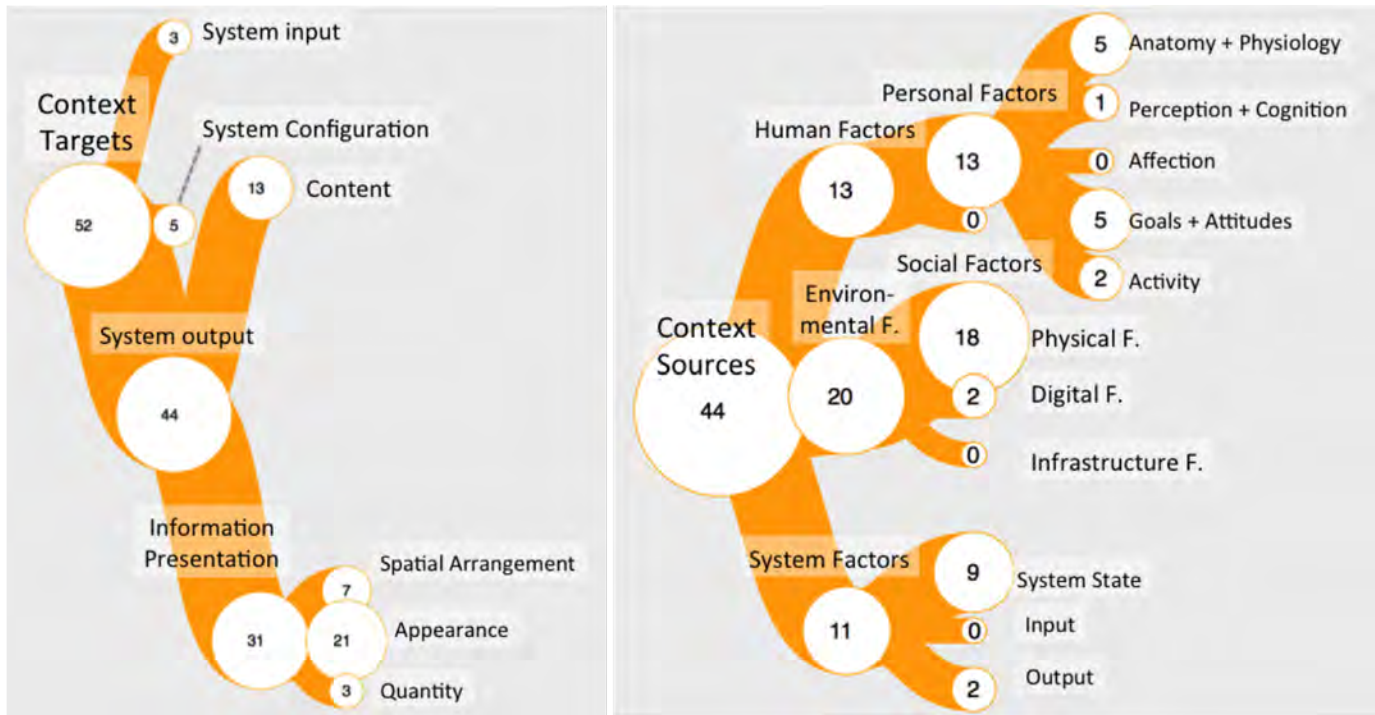


Fig. 4. Context targets (Left) and sources (Right) relevant for AR interaction. The numbers in the circles indicate the number of papers in the associated category, papers can be present in multiple categories. Interactive versions of these graphics are available under <http://bit.ly/towardspar>.

elements (e.g., increasing the size of soft buttons based on the environment, optimizing the position of user interface elements or the intensity of haptic feedback based on the information from the physical environment).

For AR, the adaptation of information presentation is an important subgroup. One of the main targets beside how the information is presented is what is presented. We summarize this context-target as content. Systems that use the content as context-target can load and display different information based on the context.

Given that AR emphasizes visual augmentation, a main target for adaption is an adapted graphical representation of the content. Here, spatial arrangement of AR content (e.g., label placement [42]), appearance changes (e.g., transparency levels [41]) or filtering of the content amount (e.g., removing labels [98] or adjusting the level-of-detail [99], [100]) have been studied. An example for adapting a complete user interface (input and output), would be an AR route navigation system, which operates by overlaying arrows on the video background at decision points. If the tracking quality degrades the depicted arrows visualization can be adapted [101]. In addition, an alternative user interface could be activated (e.g., an activity-based guidance system [102]).

### 3.6 Controller

As third major aspect of context-aware AR systems we investigated how context targets are adapted based on input from context sources. As in other context-aware systems, the adaption can be conducted implicitly through the system (adaptivity) or explicitly through user input (adaptability). While adaptable user interfaces are common (e.g., users can explicitly change the font size or user interface elements

through a settings dialogue), adaptive systems are still rare [103]. Implicit adaptation mechanisms automatically analyze context sources and adapt contexts targets accordingly based on model knowledge and rule sets. For example, a popular model for the analysis of scene content in AR is the saliency-based visual attention model by Itti et al. [104]. There are various methods, which can be used to draw assumptions about the context, including, simple rule sets, probabilistic reasoning, plan recognition, clique-based filtering or machine learning methods [103].

## 4 SURVEY ON EXISTING APPROACHES FOR CONTEXT-AWARE AR

While our vision of Pervasive Augmented Reality has not been implemented yet, there are several existing approaches investigating context-awareness in Augmented Reality. In the following section we will discuss existing works in the field of context-aware AR following the taxonomy we presented. We categorize the existing works based on the context targets while giving further information on the context sources and controller aspects in the text. Some of the works appear in several sections because they apply changes to context-targets in several categories (e.g., they adapt the system input and the system output).

### 4.1 System Input

There are only a few works that look into adapting the system input by sensing the current context. One example is the work of Henderson and Feiner [105] presenting the idea of Opportunistic Controls. They adapt the interaction



Fig. 5. A context adaptive AR representation that uses the tracking confidence of the used tracker as the context source while using the visual representation of the environment information as context target (all images Hallaway et al. [94]). (Left) When the AR system is used in coarsely tracked mode it displays a world-aligned World in Miniature, which is less affected by tracking errors. (Right) In accurate tracking mode the labels are visually registered in the physical environment. In this mode the system is highly sensible to tracking errors.

implemented in a tangible interface based on the appearance of the environment. The system utilizes existing physical objects in the user's immediate environment as input elements. When the current interaction requires a button or a slider, the system senses the current environment using the information from a depth camera as a context source. The system then detects objects in the environment whose shapes match a button or slider. The system augments these object with a virtual representation of the button or slider while the shape of the physical object provides tangible feedback.

Grubert et al. investigated hybrid user interfaces, a combination of AR and alternative user interfaces (e.g. Virtual Reality - VR). These hybrid user interfaces were investigated for interacting with a printed poster in mobile contexts [106]. The authors propose to allow users to explicitly switch between AR and alternative user interfaces but also discussed the possibility to detect when a user moves away from a poster (through analyzing tracking data) and subsequently automatically switching between AR and alternative interfaces (such as a zoomable view) [106]. Apart from applying changes to the system output by adapting the interface, the changes have also implications for the system input. For example, when in VR mode, the users can use the touch screen to interact with the system, while in AR mode the users use a cross-hair in the camera view.

Grubert et al. presented an AR system that allows to utilize multiple input modalities of wearable, body-proximate devices such as HMDs, smartwatches and smartphones [34]. Based, on the availability of devices and proxemics dimensions users can operate widgets with one device or the other. For example, a map could be panned through indirect input on an attached touchpad of a head-mounted display if used as single device. If a smartphone would be visible in the field of view of the HMD it could be used as a direct input device for panning and zooming the map, which now is visible across smartphone and HMD.

## 4.2 System Configuration

Adapting the system input is only one possible context-target. Another and probably even more important context target when talking about Pervasive Augmented Reality is the system configuration. Here, the system adapts the overall system configuration based on the current context. To date, most works in this category applied changes to the tracking configuration which is also important for future Pervasive AR applications. One example in this category is the work by Hallaway et al. presenting an AR system for indoor and outdoor environments that uses several tracking systems offering different levels of confidence in the position estimate [94]. While the focus of this work was actually adapting the interface based on the used tracker, the system also needs to adapt on the basis of the current environment and infrastructure. For example, in indoor environments, a ceiling-mounted ultrasonic tracking system offering high precision is used. However, when the users leave the area covered by this tracker the system makes use of trackers with less accuracy, such as pedometers (in combination with knowledge of the environment) or infrared trackers. In outdoor environments the proposed system makes use of a GPS sensor with inertial sensors for tracking the position.

A similar work was presented by Mulloni et al. for the purpose of indoor navigation ) [102]. The system used different sensors to track the user in indoor environments. These range from markers attached to the ground (called info points) to using integrated sensors such as gyroscope, compass, and accelerometer. If markers are present in the environment (at info points) the system uses the marker-based tracking component while integrated sensors were used between info-points.

The general problem of tracking in large and diverse environments was also identified by MacWilliams working on ubiquitous tracking for AR [107]. He presented a tracking architecture that adapts the general configuration consisting of several simultaneous running trackers with various update rates and with different precisions. The

proposed architecture consequently had to support system analysis at runtime. The system “ [...] builds on existing architectural approaches, such as loosely coupled services, service discovery, reflection, and data flow architectures, but additionally considers the interdependencies between distributed services and uses them for system adaptation” [107]. The context target is the graph that is used to connect the different trackers and represents the system configuration while the system state, and here in particular the discovered services and the data flow were used as context sources. Later iterations of a similar system but with improved performance were presented by Huber et al. [108].

Verbelen et al. presented a different work for adapting the overall system configuration with the aim to optimize the performance of a mobile AR system [109]. Differing from the work of MacWilliams, they focused on mobile AR applications where parts of the computation can be offloaded to a remote server. The overall configuration and computation of the system is adapted based on the current workload of the mobile CPU, the network quality, and the availability of remote servers that can be used to offload certain computations. Depending on the context the AR application can offload parts of the tracking computation to a server that sends back the results. Similarly, they also presented how to subtly degrade the tracking quality when the network connection is lost to meet the capabilities of the local processing power on the device. This process is hidden from the user but aims to improve the overall experience by giving the best performance in terms of tracking quality and speed.

### 4.3 System Output

By far the most existing works in the field of context-aware or adaptive AR adapt the output of the system. This could be that a different content is shown to the users, or the content is presented differently e.g., using a different interface metaphor or by changing the layout of how the content is presented depending on the context. In the following, we introduce the key works in this field based on our taxonomy.

#### 4.3.1 Content

There are several works in AR that either show different content depending on the context, or filter the displayed content to adjust the amount of displayed information based on the context. Beadle et al. for example adapt content and the visual appearance of annotations depending on user profiles [110]. In their example, they show less detailed information to children compared to adults who see a more detailed version of the displayed information and additional content. Similarly, Sinclair and Martinez created a museum guide that adapts to age categories (adults or children) [111]. Based on the type of user, the system reduces (children) or increases (adults) the amount of displayed information. The system uses the assumption that adults prefer more detail while children need less information to avoid information overload.

Another museums guide that implements a context-aware AR interface was presented by Xu et al. [112]. They used, bio-sensor readings (e.g., pulse measurements) and eye fixations as parameters for an integrated attention



Fig. 6. In MultiFi [34] the appearance of user interface widgets can be adapted based on the characteristics of employed display devices, the presence or absence of individual displays and their spatial relationship. Here, a low fidelity card widgets seen through a low resolution, low contrast head-mounted display (top) turn into higher fidelity widgets once a smartphone is superimposed (bottom).

model for AR applications in the cultural heritage domain. They adapted the visual presentation of artwork information based on an integrated “interest model”. The authors assume that the longer the user gazes towards a certain object of interest the higher is the expressed interest and the more information is requested and displayed using an AR interface. They also conceptually explained an adaption of the museum tour to guide the user to artifacts matching their interest. In addition to pulse readings and eye gaze, the authors used audio sensors to identify if the user was talking to a nearby person or concentrating on the artwork as well as to identify crowded locations. If a certain noise threshold is reached the tour route is changed and the user is guided away from the noisy location. Similarly, Barakonyi et al. presented a framework that uses animated agents to augment the user’s view [113]. The AR agents make autonomous decisions based on processing ambient environment measures such as light or sound.

Hodhod et al. presented an AR serious game for facilitating problem solving skills in children [114]. The authors adapt the gameplay based on a student model, a domain model and a pedagogical model. The student model “holds information about a student’s learning style and ability level as well as information about current effort and engagement with the game and progression through the levels. The domain model holds varied activities, hints and other elements of adaptivity that can be chosen during gameplay in response to information in the student model. The pedagogical model will hold variations in teaching style, feedback and ways of varying implicit instruction capabilities that can be modified in response to the student model. Adapting the complexity of the tasks within the AR game using these information allows to create long-term motivation. Unfortunately, the paper does not report on any achieved



results, perceived issues or technical implementation details of the adaptation process. Similarly, Doswell presents a general architecture for educational AR applications that takes into account the user specific pedagogical models [115]. These pedagogical models influence the information and explanations that are displayed to the user. Both these works relied mostly on user profiles that are explicitly assigned to adapt the system. Suh et al. present another approach that relied on user profiles [116]. Here, the user interacts with other physical objects or devices through an AR interface. For example, users can point their phone running an AR app towards the TV and see the TV augmented with individual TV interfaces. Each user can have an individual TV interface based on the user profile.

Most of these systems are aware of personal context factors or environment factors to apply changes to the displayed content. However, also digital factors were used to adapt the AR system. These can be used to overcome the problem of information clutter. For instance, one can adapt the system to the quantity of digital information that is present in an environment (e.g., the number of points of interest at a specific geolocation). Based on the amount of information, these methods reduce the number of presented information items (such as labels or pictures) or rearrange the presented information to avoid an overload of information. An example for reducing the amount of information has been presented by Julier et al. [98]. Their method uses the amount of digital information both as context source and as context target. The method divides the camera image into focus and nimbus regions. They then analyze the number of objects in the 3D scenegraph representing the digital scene for those individual regions. Based on this analysis they remove 3D objects in the scenegraph for cluttered regions. Mendez and Schmalstieg propose to use context markup (textual description) for scenegraph elements which in turn can be used to automatically apply context-sensitive magic lenses using style maps [117].

#### 4.3.2 Information Presentation

In this category, we present works where information is presented differently depending on the current context. Some work explicitly aim for adapting the interface or the visualization used, while some other are less explicit how the context information is applied to the AR interface. Stricker and Bleser for example, presented the idea of gradually building knowledge about situations and intentions of the user using an AR system to adapt the system based on these context sources [118]. As a first step, they propose to determine body posture and to analyze the user's environment. Both together are used as input to machine learning algorithms to derive knowledge about the situation and intentions of the user. Stricker and Bleser propose to use the user's activity to create an unobtrusive and adapted information presentation that fits to the user's actual needs. This could be helpful in AR maintenance or other industrial AR applications with different actions/intentions at different stages. Capturing the actions and intentions allows to automatically infer which information displayed within an AR view is currently required. However, their work entirely focuses on the context sources determining the current context by tracking of posture and environment. The output of these context



Fig. 7. Adapting to tracking error. A statistical determined average tracking error is used as adaption source to adapt the visual representation. The system highlights a physical building and two of its windows by outlining the area of the screen the objects could occupy (image by MacIntyre et al. [119]).

sources is used as input for machine learning algorithms to compute the context. However, the actual adaption and the context sources are presented conceptually only.

More explicit in their aims are the works that adapt the interface, usually based on the tracking currently used. There are several works that investigate adaption to the tracking system or use positional error estimates of the tracking system to adapt visual output. A common idea of many existing works that are sensitive in terms of tracking quality is to adapt the graphical user interface based on the error in the position estimate. We already presented the work by Hallaway et al. who presented an AR system for indoor and outdoor environments using several tracking systems offering different levels of confidence in the position estimate [94]. Using a high-precision tracker in indoor environments allowed the overlay of precisely placed labels or wireframe models within the AR interface. When the user is on an area that is tracked with less accuracy (e.g. outdoors) it is impossible to precisely overlay digital information. The proposed system consequently adapts the graphical interface by transition into a World in Miniature (WIM) visualization where the WIM is roughly aligned with the user's position coming from the less accurate trackers employed (see 5). The same group presented an approach which uses the head position as context source. Based on the head's position the augmented WIM and corresponding annotations change scale and orientation, giving it a more prominent appearance when the user looks down while reducing occlusions when looking straight forward. [120].

The work by Mulloni et al. followed a similar approach switching between different user interfaces incorporating activity-based guidance as well as indicating coarse directions using augmented arrows when the integrated sensors are used or switching to accurate overlays when at info-points supporting precise vision-based tracking [102]. Also the work on hybrid user interfaces by Grubert et al. falls into this category. They investigated AR and alternative mobile interfaces (such as a zoomable VR view) for interacting with a printed poster in mobile contexts [106]. A key observation of their research was that users might not always prefer an AR interface for interacting with a printed poster in gaming



contexts [16], [121] or even benefit from it in touristic map applications [122].

Several works adapt the presentation of the displayed content by showing more details. We already covered the work by Beadle et al. showing more content but also increasing the details of the presented content depending on user profiles [110]. Within the rehabilitation domain the work of Dünser et al. presented an AR system for treating arachnophobia (fear of spiders) by using virtual spiders overlaid in the patient's proximity [123]. Unlike previous systems in that domain using a static appearance of the virtual spider, the system adapts the graphical representation and animation of the virtual spider based on physiological sensor readings such as heart rate but also by tracking and analyzing the patient's gestures. This allows adjusting the exposure of the patients fears based on their physiological state. Unfortunately, parts of the presented work were in a conceptual state and details and how to track and analyze the patient's gestures were not provided.

Recently, Grubert et al. presented an AR system that adopts the appearance and operation of user interface widgets based on the input and output fidelities of body proximate display ecologies [34]. Body proximate display ecologies are multi-display systems (e.g., a combination of head-mounted display, smartwatch and smartphone) close to the user's body. For example, low fidelity card widgets seen through a low resolution, low contrast head-mounted display (Figure 6, top) turn into higher fidelity widgets once a smartphone is superimposed (Figure 6, bottom).

A relatively large field in AR dealing with adapting the visual presentation is view management [124]. Here, AR applications analyze the shape or structure of the environment to use it, for example, to adapt the position of augmentations. In particular, in video-based AR it is popular to use video images not only for overlaying and tracking but also for computing visual aspects about the physical environment of the user. These methods often address either the problem of information clutter or legibility. For instance, Rosten et al. introduced an approach that spatially rearranges labels in order to avoid that these labels interfere with other objects of interest [125]. For this purpose, their method extracts features from camera images and computes regions appearing homogeneous (not textured) to allow for integration of new digital content in these regions. Similarly, Bordes et al. introduced an AR-based driver assistance system, which analyses road characteristic and position of road markings as context source for adapting visual representation of navigation hints [126]. They focused on legibility of overlaid information in particular when using reflective screens for creating the AR experience (in their example the windscreen of a car). A related approach was used by Tanaka et al. for calculating the most suitable layout for presenting digital information on an optical see-through head-mounted display [127]. In their approach, feature quantities for different display regions based on RGB colour, saturation and luminance were calculated. Another related method has been proposed by Grasset et al. [42] and focuses on finding the optimal layout of labels for AR browsers. This method again uses information clutter as context source. The degree of information clutter is measured not only by using edges [125] but also by using salient regions in

general for determining regions that contain less important information [128].

Another problem that is caused by the composition of digital and physical information is reduced legibility. While legibility also depends on human factors we consider them as constant during the time of interaction. Hence, the properties of the physical scene have a major impact on the legibility. Methods that address this problem often use legibility measures as context source and adapt the information presentation as context target. For instance, Gabbard et al. suggest to analyze the legibility of labels and to adjust their presentation, such as font colors [129]. For this purpose, they performed a user study that investigated the effect of different background textures, illumination properties and different text drawing styles to analyze user performance in a text identification task. While this work does not present a fully adaptive solution to the legibility problem, the results delivered important findings about legibility as a context source. In particular, in outdoor environment text legibility is a big problem as those environments are less restricted than controlled indoor environments. In order to address this problem, Kalkofen et al. proposed to use various measures of the physical and digital environment e.g., acquired through image-based features properties of environmental 3D models, to adjust the visual parameters or material properties in an AR outdoor application [130]. Later, this idea of using different context sources for adjusting the information presentation in AR was extended by Kalkofen et al. for the concept of X-Ray AR [41]. X-Ray AR allows for instance to reveal occluded subsurface objects for subsurface visualization [40] or to see through walls [39]. One main challenge for this kind of visualization is the preservation of important depth cues that are often lost in the process of composing digital and physical information. Kalkofen et al. addressed this problem with an adaptive approach that uses different context sources in order to adjust the composition between both information sources [41].

Another important physical context factor in AR environments is scene illumination, since it may be subject to fast changes in particular in outdoor environments. In order to address this problem, Ghouaiel et al. developed an AR application that adapts the scene brightness of the virtual scene according to measures of the illumination of the physical environment (as measured through an ambient light sensor on a smartphone) [131]. Furthermore, their system adapts to the distance to a target object and to ambient noise [131]. Dependent on the Euclidean distance to a target object (e.g., a house), the authors adapted the size of the target (e.g., a label), proportionally. Finally, the authors also propose to adjust the level of virtual sound based on the ambient noise level.

Similarly, Uratani et al. propose to adjust the presentation of labels based on their distance to the user [132]. Here, the distance of labels in the scene is used as context source to change the appearance of labels. The frame of a label was used to color-code depth while the style of the frame was adapted according to their distance. DiVerdi et al. have investigated a similar concept; they use the distance of the user to objects in the physical world as input to adapt the level-of-detail of presented information [99]. Recently, this research has been extended to the usage of additional spatial

relationships in the work of Speiginer and MacIntyre [100].

MacIntyre et al. [119] analyse the statistical error of a tracking system and apply the result using the graphical representation of digital overlays as context target. The developed AR system was used to highlight objects and buildings in the environment (e.g., for navigation). The idea to overcome wrongly placed overlays resulting from the tracking error is to grow the convex hull of the digital overlay based on an estimate of the registration error. This guarantees that the digital overlay is still covering the physical object by displaying this modified convex hull and applying other visualization techniques (see Figure 7). The results of these works also influenced work by Coelho et al. when they presented similar visualization techniques but this time already integrated into a standard scenegraph implementation [133].

While not explicitly mentioning context-awareness Pankratz et al. also dealt with tracking uncertainty as context source [101]. They investigated a number of visualization concepts, which apply to route navigation systems. They indicated that error visualizations have the potential to improve AR navigation systems but also that it is difficult to find suitable visualizations that are correctly understood by users.

#### 4.4 Other

One work that demonstrates the power of context-aware AR is the work by Starner et al. [134]. This paper presents the Remembrance Agent, a body worn computer overlaying contextual information using a head-mounted display. Many of the concepts that were revisited by other groups later were presented already in this work reflected by the goal “to model the users actions, anticipate his or her needs, and perform a seamless interaction between the virtual and physical environments”. The authors discussed approaches to sense the environment, including people using cameras, analyse currently read documents as well as the users history, and use bio-sensors to model the user actions and intentions. Given that this work presented many of the ideas only in an very early stage we left it out of the detailed discussion.

Lewandowski et al. [135] focused on a mobile system for evaluating and aggregating sensor readings. They presented the design of a portable vital signs monitoring framework. The system “aggregates and analyses data before sending it to the virtual world’s controlling device as game play parameters” [135]. Also here, parts of the overall system are only presented conceptually, as this work focuses on a generic framework for aggregation sensor readings for AR but does not provide further insights on context targets (parts of the system that can be adapted) or example applications.

There are also works that deal with context-awareness but do so on a general level (e.g., merely claiming that context-awareness is important for AR). For example, Shin et al. [136] (and similarly [137], [138]) presented a conceptual work that adapts the content and the general representation with respect to the user’s profile and the user history. Caused by the conceptual character of the work no details are provided how to compute the profile and how it is exactly used as context source for adapting the system.

As stated earlier we consider all AR applications context-aware with respect to pose. This means we left out works in this survey on context-awareness that called their approach context-aware but only investigated the location or pose of the device such as the work by Liu et al. [139].

## 5 DISCUSSION

Based on the created taxonomy and the reviewed literature, in this section we discuss the current state of context-aware AR and opportunities for future research in particular for realising our concept of Pervasive AR.

### 5.1 Summary of Existing Approaches

Context-aware AR is a research niche but a defining element of pervasive AR and therefore of much interest for our work. Overall, the main problems that have been studied are related to large scale tracking (adapting the system configuration), hybrid interfaces, view management, or adaptive scene composition blending the virtual with the physical world (adapting the system output). Other directions, such as adapting the system input, have been looked at by very few works or are completely left out.

Tracking is traditionally a large research field within AR, thus the larger amount of work here is not surprising. However, most of the works use relatively simple context-sources such as location or the availability of certain trackers in the environment. Surprisingly, performance optimization was considered only in a few works (e.g., [107], [108], [109]), while battery life (a very critical topic for continuous use) was ignored.

The currently used tracking approach was also relevant in the research investigating adaptive hybrid interfaces. Depending on the tracker, the presented systems show an AR interface (when accurate trackers are available) or switch to other interfaces when less accurate pose tracking is available (e.g., World In Miniature or Virtual Reality Mode).

View management is key to make AR an unobtrusive and disappearing interface and as such also essential for our concept of Pervasive AR. So far, research looked mostly into environment factors as context-source such as salient regions in the scene, or geometrical primitives important for human perception to change the scene layout (e.g., positioning of annotations in the scene). Surprisingly, other context sources such as the current speed, current task, or human factors (e.g., stress) were not considered. In particular, these factors are important for Pervasive AR. View management could set different priorities depending on e.g. if a user rides a bike wearing a head-mounted AR display or if she keeps a stationary position while scanning the environment using the same AR display.

Adaptive scene composition is related to view management, but instead of changing the scene layout other parameters such as brightness, color or transparency of the virtual information are adapted to better match the environment or to improve scene understanding. Similarly to view management the primary context-sources found were environment factors that are usually extracted from the camera image.

Looking at the context sources that were exploited for building an adaptive AR system, most of the research focused on environmental factors of the scene that are usually extracted from the camera image such as image features (e.g., [42]), saliency of a scene (e.g. [41], [125]), or depth information from a RGBD camera [105]. Only a few works investigated human factors apart from user profiles and even less reached a prototypical development state (e.g., [112], [123]).

All of the demonstrated approaches rely on very simple context controllers e.g., by implementing an implicit adaptation using simple state machines that are often not further described or realized by explicit user input. Very few works developed more complex models e.g., using machine learning to learn different user activities [118].

To summarize, context-aware AR has been investigated only in isolated islands of topics and is not yet at the stage that allows for implementing the concept of Pervasive AR. While there is a number of conceptual works and system papers (where the state of the implementation appears unclear), complex user or context models are rarely developed and user studies on the effects of context-aware systems on the user experience of AR are generally missing.

## 5.2 Opportunities for Future Research

With respect to our vision of Pervasive AR, we see several research questions that need to be addressed to allow for a continuous AR experience through context-aware Augmented Reality. The biggest challenge is to build an AR interface that is actually context-controlled and moves away from the single purpose AR application towards a multi-purpose Pervasive AR experience. This requires not only additional context-sources but also more complex user modeling and context modeling approaches to infer the current context and user state and intentions.

There is more research needed that adapts the system configuration to actually allow for a long-term usage of the AR interface. Running an AR interface is demanding on the battery due to the used components such as cameras and sensors, and the computational performance required. We don't expect battery technology to close the gap in the near future. However, sensing the users context would allow to adapt the system to match the users task while also saving battery power. We don't need to use vision-based tracking if the accuracy is not needed for the current task but could rely on less battery-demanding sensors instead. In particular, as we are not yet able to accurately track devices with six degrees of freedom on a global scale the systems needs to switch between trackers dependent on the current environment anyway. Instead of making the decision of which tracker to use based on the availability of trackers (e.g., [94]) or the availability of fast network connections to distribute the task (e.g., [109]), one should also consider the energy consumption and battery state as context sources. For example, one could imagine a mobile simultaneous localization and mapping (SLAM) system, which balances the workload of mapping between a server and the handheld client, based on the computational resources and battery state of the client.

View management and scene composition is a topic already researched in context-aware AR. However, there

still seems to be a large potential for future Pervasive AR systems implementing a more unobtrusive interface. For example, user interface elements could be adapted to the motion of a user (e.g., label size as the user walks faster). This is even more important if we consider heads-up displays in cars or head-mounted displays for sport. Here, the current motion should have a strong influence on the AR interface.

The AR system should adapt not only to the appearance or the motion of the environment but also to the features of the environment such as the availability of other devices. For example, we have seen adaption techniques and systems for tracking of the user and system in space (e.g., [107], [108]) but we still miss adaptive systems for user input and system output. For system output we witness a recent exploration of multiple, complementary display types such as stationary panel displays and stationary projectors [32], head-mounted displays with stationary projector [33] or head-mounted displays with handheld and wearable touch displays [34]. However, all those systems focus on a single, well-defined use case. We envision spontaneous display binding according to which displays are currently available in a context of use and on current user needs. Imagine a user walking into a smart meeting room, who can extend her personal view in an HMD or on a smartphone with peripheral projections. When leaving the room she could still complement the field-of-view of her smartwatch with an HMD. The required display discovery and association would need extended software infrastructures beyond what is available for tracking systems today. Similar, the presence or absence of interaction devices and modalities should be seamlessly integrated into the interaction space of users. First approaches exist outside of the AR domain, e.g., cross-device development toolkits providing different input modalities to users [140], [141]. Still, these approaches should be adopted for the use in highly dynamic usage environments.

Also, AR systems should minimize the effort for manual calibration steps from users. Specifically, the use of optical see-through head-mounted displays still often requires uncomfortable calibration procedures (e.g., [142], [143]). First approaches for semi-automatic [144], [145] and fully automatic [146], [147] optical see-through (re)calibration methods have been explored and should be built upon in the future.

Finally, a Pervasive AR interface needs to be socially and privacy aware. The lessons learnt from Google Glass showed that this is critical when similar technology is released to the public [148]. Depending on the context, we for example might need to automatically switch of the camera because it's affecting the privacy of people in our proximity. Similarly, input capabilities need to be adapted because the current social context does not permit voice commands or hand-gestures.

Most of these problems require more complex user modeling and context modeling approaches than employed in todays AR systems. The context-controllers found currently in context-aware AR are too simplistic to model or infer detailed contexts. More complex models could come from other research communities such as user modeling and machine learning [103]. However, more complex context

controllers might also require more context sources than demonstrated in AR to date. As already stated, many context-aware AR approaches use environmental factors only. Consequently, the AR systems typically have knowledge about the environment but to a lesser extent about knowledge about the user. Other sensors for measuring context sources such as gaze-trackers, velocity sensors, heart rate monitors, or pedometers are widely ignored in AR, but could give valuable input to allow for e.g. context-controlled application switching, task-driven battery optimization or adjusting privacy settings, all contributing to the implementation of the concept of Pervasive Augmented Reality.

## 6 CONCLUSION

In this paper, we introduced the concept of Pervasive Augmented Reality (PAR) as a continuous, context-aware Augmented Reality experience. We gave an overview on the current state of context-aware AR as the main conceptual building block towards PAR. We developed and presented a taxonomy based on three top-level domains: Context sources, context targets, and context controllers. We further explored possible categories within the top-level domains of sources and targets by specifically focusing on the unique aspects of a PAR system. After the identification of possible domains and following our taxonomy we reviewed existing research in the field of PAR and identified opportunities for future research. Pervasive Augmented Reality has the potential to significantly change the way we interact with information and our surrounding environment. In this article we haven't explored social or privacy considerations neither have we discussed every-day, practical implications of a context-aware, continuous AR experience. Our focus of attention was directed towards technical, technological, and selected perceptual and human factors. It is apparent that PAR is still in its infancy. However, current developments in AR hardware and software, like head-worn displays with integrated computing and sensing capabilities will lead to research and implementations towards Pervasive Augmented Reality. We hope, with this article we could lay some of the foundations for a systematic approach towards Pervasive Augmented Reality.

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