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12.09.2016

Sensor-supported Game Mechanisms for Augmented Reality

Bachelor’s Thesis

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**Abstract.** bla

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# Background

## Introduction

Augmented Reality is bigger than ever before. The recent success of the game Pokémon GO, coupled with advancements in the related domain of Virtual Reality, has spurred popular interest in the combination of real and virtual content which has long been an area of academic interest. Microsoft’s HoloLens, a Mixed Reality HMD (head-mounted display), a development version of which was released in 2016, shows great potential despite a currently high price point.

This thesis seeks to provide an introduction to relevant topics before discussing a framework for sensor-supported Augmented Reality games. First, definitions and approaches to Augmented Reality are presented with examples of existing applications in the fields of education and expertise transfer, industrial use, and video games, followed by a brief discussion on the potential and limitations of the medium. Afterwards, the paper goes into sensor technology and applications, with a special focus on video games, and finally design patterns. In the second half, a framework for sensor-supported Augmented Reality is conceived of and partially implemented in the Unity game engine for the Microsoft HoloLens.

## Motivation

This thesis builds on the work the author performed during an internship at the Open University of the Netherlands, as part of the WEKIT project. WEKIT (Wearable Experience for Knowledge Intensive Training) is a European research project that aims to develop a new approach to expertise transfer by means of wearable technology, presented through task-sensitive Augmented Reality (“What is WEKIT?,” n.d.). During this internship, the author was able to familiarize himself with topics such as Augmented Reality and the combination of various sensors.

A focus group survey (see appendix) was conducted in preparation for this paper, in order to ascertain whether there was demand for research into these topics and what should be the goal of such research. 18 participants were involved – current and former game design students, as well as one professor for game design, with game development expertise ranging from one year to four or more. This revealed interest but inexperience in the usage and development of augmented reality applications; although all but one of the participants knew the term Augmented Reality, only half of them reported having used AR applications before and only three out of the 18 participants had experience developing them, however 12 of the remaining 15 expressed interest in doing so. Despite this, the participants showed mixed (though generally positive) expectations of the field in regards to both the gaming industry in general and education in particular: When asked whether Augmented Reality games would be important in these domains in the future, both averaged a score of 3.388… on a Likert scale from 1 (disagreement) to 5 (agreement). The response to whether they thought using additional sensor data could improve Augmented Reality applications, especially data relating to the user such as data on movement or body posture, was more uniformly positive, averaging a score of 4.388…, although some participants noted a lack of knowledge of sensor technology.

This combination of interest offset with lack of experience and skepticism towards the future suggested that an investigation into the prospects of augmented reality gaming and systematic guidelines towards the design of AR gaming applications could prove beneficial to current game design students.

## Related Work

Fields of research that overlap with Augmented Reality include Virtual Reality (which puts the user into a completely virtual environment) or the broader term of Mixed Reality; ubiquitous and wearable computing, as well as the internet of things (See Mattern & Floerkemeier (2010)) all allow users to interact more broadly with their environments, to which ends a variety of sensors may be used.

According to Lamantia (2009) “the convergence of mobile computing and wearable computing with augmented reality is naturally of great interest to interaction designers who are interested in the rise of everyware” (“Augmented Reality: A Thumbnail Sketch” para. 2), while Papagiannakis, Singh, & Magnenat-Thalmann (2008) similarly refer to “the convergence of wearable computing, wireless networking and mobile AR interfaces” as bringing about “a new breed of computing called ‘augmented ubiquitous computing’” (p. 1).

Some Augmented Reality Games may also be categorized as Pervasive Games, Location-based Games, or both, though the former does not require technology and the latter is primarily occupied with spatial characteristics (Wetzel, 2013, p. 1).

Pattern languages, as discussed in section 2.3, exist across a variety of fields, such as architecture and software engineering. In the case of e.g. the latter and Augmented Reality, there is also the more general field of Human-computer interaction (HCI).

# Literature review

This section comprises a summary of literature on the topics of Augmented Reality, sensors and design patterns. The content was selected first through online searches for possible areas of interest, such as the topics mentioned above, more specialized areas like AR visualization, related topics like the internet of things, and various combinations of all of the above. The author was also directed towards specific topics by the examiners of this paper. From there, the search shifted to references used in the above sources, and so on.

This section does not attempt to present a comprehensive overview of any of its topics, as doing so would be out of its scope. It does however mention papers that go more in-depth.

## Augmented Reality

In 2011, the NMC Horizon Report stated that “Augmented reality, a capability that has been around for decades, is shifting from what was once seen as a gimmick to a bonafide game-changer” (L. Johnson, Smith, Willis, Levine, & Haywood, 2011, p. 16). Since then, the availability of Augmented Reality, or AR, applications on consumer-grade devices such as smartphones has been driving the field forward, as referenced by researchers like Munnerley et al. (2012) (“The fact that these new layers can be accessed with consumer-level mobile devices means that they offer a uniquely open way to enrich environments and offer multiple, flexible learning opportunities” (p. 41).) and Specht, Ternier, & Greller (2011, p. 117).

This section will first present a number of definitions and taxonomies for Augmented Reality, before listing examples from the educational, entertainment and commercial sector.

### Definitions and classifications

The term Augmented Reality was first used by researcher Tom Caudell in 1992, according to e.g. Olshannikova, Ometov, Koucheryavy, & Olsson (2015, p. 18), however it has retroactively been applied to older work (“The functional and experiential concept originated with the head-up instrument displays and targeting devices airplane manufacturers created for military pilots shortly after World War II” (Lamantia, 2009, "Augmented Reality: A Thumbnail Sketch" para. 1).) and there exist a multitude of definitions.

A frequently cited general description of AR utilizes the Virtuality Continuum by Milgram & Kishino (1994), which places real environments on the left, virtual environment environments on the right, and Augmented Reality left from the center (under the umbrella term of *mixed reality*, which also includes *augmented virtuality*).



Figure 1: Milgram & Kishino’s Virtuality Continuum

Similarly, L. Johnson et al. (2011) refer to AR as ”the addition of a computer-assisted contextual layer of information over the real world, creating a reality that is enhanced or augmented” (p. 16).

More detailed classifications show some differences. As FitzGerald et al. (2013) point out, early research focused on “the use of AR as a primarily graphical display” (p. 44). For example, Azuma (1997) defined Augmented Reality applications as:

1. Combining real and virtual
2. Interactive in real time
3. Registered in three dimensions

However, over time definitions have undergone numerous changes. Just four years later, Azuma et al. (2001, p. 34) instead listed the following qualifiers:

* Combining real and virtual objects in a real environment;
* interactive, and in real time;
* registering (aligning) real and virtual objects with each other.

While both papers mention that Augmented Reality may apply to all senses, they only do so briefly, as research had at this point been focused on optical applications. As the field advanced, applications including other senses became more commonplace and classifications were adjusted accordingly. For example, FitzGerald et al. (2013)’s working definition of AR includes “the fusion of any digital information with physical world settings, i.e. being able to augment one’s immediate surroundings with electronic data or information, in a variety of formats including visual/graphic media, text, audio, video and haptic overlays” (p. 44). Munnerley et al. (2012) specifically argue for a broad definition of Augmented Reality: “There is no need for such augmentation to be limited to the provision of visual information” (p. 41). Calo et al. (2015) concede that “there is no easy definition of ‘augmented reality’” and list as features, “most of which are present in most AR systems” (p. 3) the following:

* Sense properties about the real world.
* Process in real time.
* Output (overlay) information to the user.
* Provide contextual information.
* Recognize and track real-world objects.
* Be mobile or wearable (pp. 3-4).

(Although Calo et al. acknowledge that not all Augmented Reality systems are mobile or wearable (and that this attribute is not necessary for something to be considered AR), they express confidence that mobility will be increasingly common in the future (p. 4).)

Examples of Augmented Reality utilizing senses other than sight include Ternier, De Vries, Börner, & Specht (2012), whose application for cultural sciences students’ field trips focused on audio augmentation, arguing that “just like a user should - while driving a car - use sight as much as possible to drive, we believe that with location based learning, a learner’s eyes must be primarily used to examine the environment” (§ 1 para. 2). Benko, Holz, Sinclair, & Ofek (2016) developed two systems that give haptic feedback corresponding to virtual objects (NormalTouch und TextureTouch) and although they used it for virtual reality (where the user moves around in an entirely virtual environment), the possibility of AR applications is brought up (“Introduction” para. 4).

Although a trend can be observed, there exist outliers. “A Dictionary of Media and Communication” (Chandler & Munday, 2011) still lists Augmented Reality as "Vision technologies that superimpose a computer-generated object on an image of a real-world scene", while one of the earlier attempts at classifying AR (Milgram & Kishino, 1994) also mentions haptic and vestibular AR not just in passing but as “natural [modes] of operation” (p. 6).

Specht et al. (2011) are critical to over-generalization, stating that “we find these definitions too generic and in direct conceptual conflict with closely related systems such as context-aware or immersive systems, mixed reality, and personalized adaptation” (p. 117). It should however be noted that their working definition still includes senses other than vision, being “a system that enhances a person’s primary senses (vision, aural, and tactile) with virtual or naturally invisible information made visible by digital means. . . . where ‘view’ also includes other primary human senses” (p. 117).

Another venue for discussion is the role of real environments, reflecting Augmented Reality’s place on a continuum without easily definable borders. Azuma et al. (2001) bring up applications that “require removing real objects from the perceived environment, in addition to adding virtual objects. . . . Some researchers call the task of removing real objects mediated or diminished reality, but we consider it a subset of AR” (p. 34). Similarly, Wetzel, McCall, Braun, & Broll (2008)question whether the game “The Eye of Judgement” is in fact Augmented Reality, since, although physical playing cards recognized by a camera serve as input, “the real playing field is never seen on the screen as it is completely overlaid by virtual characters and objects” (p. 177). Bringing up discussions about the seemingly disappearing borders between Augmented Reality and Virtual Reality, Schell (2015) predicts that “by 2025 we’re going to have VR things and we’re going to have AR things. . . . because you want them both to be good and to be good they’re going to need to use different technologies and systems” (20:32).

### Approaches

This section is concerned with the ways in which Augmented Reality systems have been and can be constructed. It differentiates between technology and augmentation basis, loosely based on the distinction Bower, Howe, McCredie, Robinson, & Grover (2014) make between basic hardware requirements and “other technologies” (p. 2) with which Augmented Reality experiences may be improved. Generally, the approaches discussed in section 2.1.2.1 server as the basis for augmentation (ways in which information is transferred from the outside world to the AR system), while the technologies in section 2.1.2.2 serve to transfer information from the device to the user.

This distinction is not perfect, as there is some overlap between the categories. For example, Azuma et al. (2001) group both displays, which are discussed in 2.1.2.2, and tracking, which is a subject of 2.1.2.1, under the category of “enabling technologies”, while Papagiannakis et al. (2008) make a distinction between “technological characteristics” and “the applicability in different environments like indoor or outdoor” (p. 9), both of which would fall under Technology under the chosen classification. Despite this, for the purposes of this thesis at least, the present categorization should serve to provide some structure.

#### Augmentation Basis

There are fundamentally two different approaches to Augmented Reality: Location-based and vision-based.

Location-based (also known as geolocated, marker-less or gravimetric (FitzGerald et al., 2013; L. Johnson et al., 2011; Munnerley et al., 2012)) AR outputs information based on the user’s position. According to Munnerley et al. (2012), Points of Interest (POI) are defined and associated with virtual assets – “When a user . . . explores a space the POIs are revealed and the content can be accessed” (p. 44). This exploration can be based solely on location – usually provided through GPS – as in the application by Ternier, De Vries, et al. (2012), or take into account user orientation for increased precision (Hol, Schön, Gustafsson, & Slycke, 2006).

Vision-Based (also known as artefact-based or marker-based) (FitzGerald et al., 2013; Munnerley et al., 2012) Augmented Reality functions by using computer vision techniques to identify and track patterns known as fiducials in the environment. You & Neumann (2001) name as examples for fiducials corner features, square shape markers, circular markers and multi-ring color markers (§ 5.1), while Munnerley et al. (2012) refer to barcodes and QR codes and go on to state that “recent developments in image recognition and mobile technology allow for any image to be used as a marker as long as it is pre-defined in the AR code” (p. 44). Papagiannakis et al. (2008) differentiate between these passive markers and active fiducials like light-emitting diodes (p. 9).

Both of these approaches have their advantages and disadvantages: Fiducials can only be used if the system has been trained to recognize them and conditions like inadequate lighting do not interfere with them (though Papagiannakis et al. (2008, p. 10) mention that using infra-red lights can vastly improve tracking quality) and thus vision-based approaches are generally best suited to prepared environments. Meanwhile location-based systems can suffer from inaccuracy or loss of tracking (for example GPS does not work indoors) – marker-based tracking can be a “much more stable and a simple yet often times effective solution” (Wetzel et al., 2008, p. 178).

Possible solutions lie in the use of hybrid systems as described by Schall et al. (2009) or image understanding, which Furmanski, Azuma, & Daily (2002) explain “attempts to recognize structures and features with the aim of automatically describing the contents of an image” (§ 4 para. 1). The Microsoft HoloLens takes a somewhat related approach: By utilizing a depth camera and tracking head movement through various sensors, a technique called “spatial mapping” (“Spatial mapping,” n.d.) can be used to construct a virtual three-dimensional model of the users’ surroundings, determine their position therein, and display virtual content at the appropriate coordinates, all without the need for markers.

#### Technology

Sutherland (1968) is frequently considered to have created the first true Augmented Reality display (Calo et al., 2015; Feiner, MacIntyre, Höllerer, & Webster, 1997). The way his device differs from later Augmented Reality platforms highlights several areas of interest.

Firstly, there is the distinction between mobile and stationary (or desktop) AR. Though Sutherland’s display was restricted by the technology of the time, he stated that “eventually we would like to allow the user to walk freely about the room” (p. 760), leading FitzGerald et al. (2013) to state that “developers have always aimed to make AR portable” (p. 45). Calo et al. (2015) went so far as to include mobility in their list of features of AR (see section 2.1.1), explaining that “in the long term, we expect that many augmented reality systems will be wearable. . . . However, a system does not need to be wearable to technically be considered an AR system” (p. 4).

The first truly mobile Augmented Reality system, or MARS, (Mulloni, Dünser, & Schmalstieg, 2010; Papagiannakis et al., 2008) was the Touring Machine by Feiner et al. (1997), which allowed the user to walk around relatively unconstrained, by wearing a backpack and a head-mounted display.

A topic which is closely related to this is type of display. The main distinction to make in this regard is between video see-through and optical see-through. (See Azuma (1997) for a discussion on the advantages and disadvantages of these). Optical see-through refers to the projection of information while still affording the user a view of the real world. Video see-through displays on the other hand provide no direct view of the real world; instead, cameras are used to record the outside world, the video is combined with visual augmentation and the result displayed. A method which might be considered optical see-through but is not as easily classified, functions by projecting information directly unto the world (outside of the device itself). A few systems have achieved this by simply using commercial projector technology (Ishii, Wisneski, Orbanes, Chun, & Paradiso, 1999; Yamabe & Nakajima, 2013), an approach which is only suitable if secrecy is not required since it makes the information visible for anyone and additionally doesn’t allow multiple users to see different images. Ishii et al. (1999) further note that their projector’s brightness was insufficient, requiring them to darken the room (p. 4). Azuma et al. (2001) bring up reflective systems that do allow multiple users to see different images, while making the information visible only along the line of reflection; however this requires objects in the world to be coated with retroreflective material, further reducing its applicability in mobile AR (p. 35). While Kruijff, Swan II, & Feiner (2010) still mention projector-camera systems, the majority of dedicated Augmented Reality systems developed today seem to utilize other kinds of display technology, as demonstrated by Calo et al. (2015)’s list of “some specific examples of AR being marketed or developed today” (p. 3) not including any such setups.

While most devices listed by Calo et al., as well as Sharma, Wild, Klemke, Helin, & Azam (2016) are head-worn displays (also referred to as head-mounted displays (HMDs)), other types of displays such as hand-held and wrist-worn ones have also been used (Papagiannakis et al., 2008, p. 11), most notably smartphones (see section 2.1.3 for various examples).

### Applications

Here, some examples are delineated of how Augmented Reality has been applied. Specifically, this part of the paper looks into educational and game applications, as well as commercial and industrial applications in general. This is only exemplary, as Augmented Reality has also been applied in other contexts such as the military and medical domain. To cover a wider field of applications or give more examples of each would however fall outside the scope of this thesis.

#### Commercial

A large number of examples of industrial applications have already been gathered (Azuma, 1997; Azuma et al., 2001). The section is therefore focused on more recent commercial uses of AR.

Without going into detail, Calo et al. (2015) list as domains in which AR has been applied “hands-free instruction and training, language translation, obstacle avoidance, advertising, gaming, museum tours, and much more” (p. 1). Henderson & Feiner (2009) additionally refer to maintenance and repair as “an interesting and opportunity-filled problem domain for the application of augmented reality” (p. 135), citing not only an abundance of previous work but also bringing up the existence of a number of consortiums dedicated to this field of research (p. 136). The paper by Henderson & Feiner (2009) is itself an example of successfully applying Augmented Reality to the maintenance sector: Mechanics equipped with a head-mounted AR display were able to locate tasks more quickly than those using a more traditional static screen and while task completion time did not differ significantly, the researchers found that their approach reduced overall head movement which could provide health benefits.

Nilsson, Johansson, & Jönsson (2009) conducted a study in which AR was used to support collaboration between rescue services, police and military. Presented with forest fire scenarios, the users were able to place icons on an Augmented Reality map to coordinate their strategy. Participants gave the AR system equal or higher scores than a conventional paper map and qualitative research revealed interest in applying Augmented Reality to other tasks within the three groups.

The field of Obscured Information Visualization (OIV) (Furmanski et al., 2002) has previously been used to make visible “underground infrastructures, such as water mains and electricity lines” (Schall et al., 2009, § 5 para. 1) and could potentially be applied to a wide array of maintenance tasks.

Although it had at this point not yet been applied, Olshannikova et al. (2015) propose to make use of AR in Big Data visualization, stating that it “might solve many issues from narrow visual angle, navigation, scaling, etc. For example, offering a way to have a complete 360-degrees view with a helmet can solve an angle problem” (p. 18).

#### Education and expertise transfer

As Radu (2014) states, throughout its history “a relatively high amount of research studies have investigated the potential impact of augmented reality to benefit student learning” (p. 1533), demonstrating a high interest in this domain. In 2009, Dunleavy, Dede, & Mitchell (2009) named Augmented Reality as one of three kinds of technological interfaces “now shaping how people learn,” along with “the familiar ‘world- to- the- desktop’ interface,” and multi-user virtual environments (pp.7-8). The 2011 NMC Horizon Report (L. Johnson et al., 2011) estimated a time of 2-3 years until mainstream adoption of Augmented Reality as a tool for “teaching, learning, or creative inquiry” (p. 4). Interestingly, the same estimate was repeated in the 2016 Higher Education Edition of the Horizon Report (L. Johnson et al., 2016), showing that despite the academic interest, Augmented Reality has not managed to completely ground itself in education, though the report does express optimism that increasing ease of use will drive this development forward (p. 40).

Due to the abovementioned interest in Augmented Reality for learning, there have been not only a number of studies on the subject but also several meta-reviews and overviews (Bower et al., 2014; Fitzgerald, Taylor, & Craven, 2013; Radu, 2014). Radu (2014)‘s overview of areas that have been shown to benefit from Augmented Reality applications includes learning spatial structure and function, learning language associations, long-term memory retention, improved physical task performance, improved collaboration, and increased student motivation (pp. 1534-1536).

Arguments as to why learning environments benefit from Augmented Reality have been proposed in multiple papers. As FitzGerald et al. (2013) point out, “augmenting/adding to reality has always been a part of outdoor education” (p. 49) and using Augmented Reality technology to these ends is a logical next step. Radu (2014) compares various media in regards to educational affordances and comes away with the following factors as influencing learning in AR:

* Content is represented in novel ways
* Multiple representations appear at the appropriate time/space (spatial/temporal contiguity effect)
* The learner is physically enacting the educational concepts (“Research shows that physical activity is linked to conceptual understanding of educational content: Shelton and Hedley, in their studies of spatial learning in AR, hypothesize that visuospatial comprehension is enhanced by physical interaction with 3D content.”)
* Attention is directed to relevant content
* The learner is interacting with a 3D simulation: (“Digital simulations in general are effective tools because they allow students to experience phenomena that are impossible or infeasible to experience otherwise . . ., they are dynamic and interactive allowing student control over the educational content . . ., and they scaffold and assess user learning.”)
* Interaction and collaboration are natural (pp. 1539-1540).

There is some overlap between this list and Dunleavy et al. (2009)’s enumeration of unique affordances of AR: “The greater fidelity of real world environments, the ability of team members to talk face-to-face with its bandwidth on multiple dimensions, and the capacity to promote kinesthetic learning through physical movement through richly sensory spatial contexts” (p. 8). Furthermore, Ternier, Klemke, Kalz, van Ulzen, & Specht (2012, pp. 2144-2146) cite the concept of immersive learning (Dede, 2009) as an important background in the development of their mixed reality framework . Although Bower et al. (2014) criticize past efforts towards Augmented Reality learning (“This can lead to the situation where Augmented Reality only develops lower order thinking skills by supporting understanding and application, without encouraging higher order integrative thinking skills such as analysis, evaluation and creation” (p. 7)), they acknowledge its potential and recommend students be given design tasks in order to make better use of it. Schmitz, Specht, & Klemke (2012) mapped a number of game design patterns to cognitive and affective learning outcomes in Augmented Reality games for learning; similarly, Dunleavy (2014)’s literature review revealed three design principles for learning-oriented AR – “Enable and then challenge”, “drive by gamified story”, and “see the unseen” (p. 29).

#### Augmented reality games

Games are an application particularly suited for the medium of Augmented Reality. As L. Johnson et al. (2011) state: “Augmented reality is an active, not a passive technology” (p. 17). FitzGerald et al. (2013, p. 44) somewhat similarly emphasize the “dialogue between the media and the context in which it is used.” Although commercial AR games can be said (Wetzel et al., 2008, p. 4) to go back as far as 2003’s EyeToy, efforts were for a long time focused on research, until the advance of smartphone technology, which made devices with Augmented Reality capabilities widely available (see 2.1), gave developers a venue (Wetzel, 2013, § 1 para. 1); however, according to Wetzel, knowledge about how to best approach the design of AR games was still lacking, a sentiment Antonaci, Klemke, & Specht (2015) share: “Little is known on how to systematically apply game-design patterns to augmented reality” (p. 3). Similar to these sources, Dunleavy (2014) attempted to extrapolate design guidelines from the AR game Dino Dig, which despite having educational content was primarily intended to entertain.

One approach to the design of Augmented Reality games is concerned with translating existing games into this new medium. PingPongPlus (Ishii et al., 1999) uses microphones to locate the ball’s points of impact on a ping pong table and utilizes a projector to augment the game according to one of several different game modes that go beyond the original game, for example by encouraging players to cooperate. Specht et al. (2011)‘s Locatory is an AR adaptation of the game Memory, requiring players to find virtual cards spread around the environment and then match them to real landmarks. Most recently, Pokémon GO (Niantic, 2016), an Augmented Reality game based on the well-known Pokémon franchise and Ingress (Niantic, 2013) (cited by Wetzel (2013) as a rare example of a mobile AR game with a large player base (§ 2.1)), released to great success, breaking download records (Crecente, 2016). On the other hand, Wetzel et al. (2008) criticized AR card game The Eye of Judgement, stating it did “not map well to augmented reality. . . . as the game only tries to be visually more appealing than the originals but does not include genuine engaging game play” (p. 178).

### Outlook

This section provides an overview over the potential of AR and what challenges it will need to overcome in order to realize it.

#### Possibilities

Several qualities of Augmented Reality may allow it to take a major role in society. As noted above, a multitude of applications have already been tested or proposed in the commercial and educational sectors. This section highlights some more general qualities.

**Engagement and motivation**: Several studies have pointed to Augmented Reality as being engaging and motivating particularly for learning (Radu (2014): “Users report feeling higher satisfaction, having more fun, and being more willing to repeat the AR experience” (p. 1536).). Dunleavy et al. (2009, p. 18) found that students who had previously shown a lack of interest in their studies showed a significantly altered behavior and increased engagement when interacting in Augmented Reality. Schmitz et al. (2012) also mapped motivational effects to the game design pattern of Augmented Reality, as demonstrated in a number of studies: “Students feel ‘personally embodied’ in the game. Their actions in the game are intrinsically motivated (Rosenbaum et al., 2006). Learners are attentive (Wijers et al., 2010). Students are mentally ready for learning (Schwabe and Göth, 2005)” (Table 1).

**Societal**: Calo et al. (2015, p. 5) point out how Augmented Reality might influence people’s experiences; not only those of the AR users but also those around them, “whose features and actions may now be recorded and analyzed”, as well as allowing multiple people to “perceive the same environment differently.” They specifically mention the capability of Augmented Reality to replace disabled people’s senses.

**Other**: Dunleavy (2014, p. 30) refers to the interdependent work in physical spaces which AR allows as “the most frequently reported affordance of AR (Dunleavy, Dede, & Mitchell, 2009; Facer, Joiner, Stanton, Reid, Hull, and Kirk, 2004; Klopfer and Squire, 2008; Squire, 2010; Perry et al., 2008; Squire, Jan, Matthews, Wagler, Martin, Devane and Holden, 2007).”

#### Limitations

Azuma et al. (2001, p. 43) see three groups of obstacles Augmented Reality has to overcome: technological limitations, user interface limitations, and social acceptance issues. The author will attempt to expand on the examples given in the same source.

**Technological**: Although some limitations listed by Azuma et al. have been solved or reduced, some persist and new ones have been discovered. Kruijff et al. (2010) present an extensive catalog of issues, categorized as relating to the environment, capturing, augmentation, display, and individual user difference. Though these are stated to be based on visual processing and interpretation, the categorization also holds for location-based AR.

For instance, Dunleavy et al. (2009) mention inadequate weather conditions as restricting their studies (p. 14). FitzGerald et al. (2013, p. 51) similarly cite a need for displays that can be read in bright sunlight and devices that function in the rain, and refer to local environmental conditions as decreasing the accuracy of cheap geolocation tools while more advanced tools are costly. Another issue relates to the inaccuracy or unavailability of GPS systems indoors, and in the case of Ternier, De Vries, et al. (2012), the infrastructure of the city of Florence led to tracking issues even outdoors (§ 3 para. 6).

Biocca & Rolland (1998) investigated the effects of visual displacement, a result of the cameras used in video see-through displays not existing at the same location as the displays, calling such intersensory conflicts and the resulting adaptation “among the most critical issues in the design of immersive virtual environments” (p. 262). They report noticeably worse performance during hand-eye coordination tasks, as well as negative aftereffects. However, since modern technology allows cameras and displays to be located much closer together (in Biocca & Rolland’s study there was a displacement of 62 mm upward and 165 mm forward), this effect of visual displacement can be reasonably expected to be significantly reduced.

The task of correctly aligning real and virtual objects, known as the registration problem, is another one that has not yet been solved, despite it being “one of the most researched areas in AR” (Specht et al., 2011, p. 118). According to Azuma (1997), this task is necessary both for maintaining immersion and performing applications that require accuracy and thus “without accurate registration, augmented reality will not be accepted in many applications” (p 367).

**UI**: Problems related to user interfaces surfaced in many of the papers found during the literature review and can be separated into how information is displayed and how users interact with it.

Furmanski et al. (2002) investigated how to avoid depth ambiguity when visualizing obscured information and found that people tended to still rely on occlusion. Julier et al. (2000) noted that “if a graphics-based AR system is to be effective, care must be taken to ensure that its display is not cluttered with too much information” (p. 1) and developed a filter technique for this purpose. Dunleavy (2014, p. 29) similarly pointed out that “one of the most frequently reported AR design challenges is preventing student cognitive overload during the experience (Dunleavy et al., 2009; Klopfer and Squire, 2008; Perry, Klopfer, Norton, Sutch, Sanford, & Facer, 2008).”

Several studies, such as that by Specht et al. (2011, p. 125), report users developing tunnel vision and thus losing sight of their real surroundings when using AR, which included participants overlooking cars. Dunleavy (2014) expresses that in addition to the risks associated with this phenomenon, applications that intend the user to observe the environment may suffer from it, emphasizing the design metaphor of “the mobile device as a lens rather than a screen” and that “the technology needs to drive the students deeper into the authentic observation and interaction with the environment and with each other if AR is to grow beyond a novelty technology” (p. 32).

Tunnel vision is brought up by Lamantia (2009) as one of the “gaps in the interactions current AR experiences support.” The full list consists of

* Loner (“Reliance on single-person, socially disconnected user experiences.”)
* Secondhand Smoke (“Indirect experience of augmented reality.”)
* Pay No Attention to the Man Behind the Curtain (“AR experiences that identify people by face, marker, or RFID tag could severely challenge our ability to do ordinary things.”)
* The Invisible Man! (“AR experiences might take active measures to reinforce social mechanisms such as privacy or anonymity by actively altering the mixed-reality environment.”)
* Tunnel Vision (“Limiting their ability to react to stimuli beyond their narrow, monocular view.”)
* AR for AR’s Sake (“Developing interaction patterns that address these everyday activities is essential.”)

Generally, Radu (2014) notes that oftentimes participants find Augmented Reality more difficult to use than equivalent systems, although he does note that apparently this does not negatively impact motivation.

From a legal angle, Calo et al. (2015) names as “issues related to display of information” negligence, product liability, digital assault, and discrimination (p. 7).

**Social acceptance**: Augmented Reality systems necessarily need to gather data about the user and their surroundings. This can present a problem for “users who are not aware exactly what data is being collected or who are wary of being tracked or targeted by companies which provide personalised marketing (Hamilton, 2012)” (FitzGerald et al., 2013, p. 52). More precisely, Calo et al. (2015) list the following “issues related to the collection of information”:

* Reasonable expectations of privacy
* The third party doctrine
* Free speech
* Intellectual property (p. 6)

**Other**: Another concern brought fourth by some researchers (Dunleavy et al., 2009, p. 18; Wetzel et al., 2008, p. 173) is the notion that one of the factors responsible for the positive reception of AR by users is the novelty effect and that this may fade as people become more accustomed to Augmented Reality.

Finally, Radu (2014, p. 1541) stresses the investments and training necessary for Augmented Reality to be used in education – mirroring similar statements by Olshannikova et al. (2015, p. 21) about AR for Big Data Visualization – and brings up the issue, neglected in the other papers surveyed as part of this literature study, of the bigger spaces Augmented Reality may require compared to traditional computer experiences.

## Sensors

Sensors are a prerequisite for Augmented Reality and the choice of sensors enables different kinds of applications, such as the use of a GPS system for geolocated AR. This sections will first give a brief definition of what sensors are and afterwards delve into the use of sensors in gaming and Augmented Reality respectively.

The Merriam-Webster dictionary defines a sensor as “a device that responds to a physical stimulus (as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control).” (“Sensor,” n.d.)

Dasarathy (1997) points to a more general definition of a “sensor as a source of information” (p. 26), which would include human sensors, but clarifies that this would make rigorous analysis much more difficult. Dasarathy also makes a distinction between three types of sensors: Active, passive, and mixed active/passive. A more in-depth classification was proposed by White (1987), based on measurands, technological aspects, detection means, conversion phenomena, sensor materials, and fields of application. Coming from an expertise transfer background, Sharma et al. (2016) mapped high level functions to low level functions and the latter to associated sensors. The paper also provides an overview of “the state-of-the-art sensors in terms of their technical specifications, possible limitations, standards, and platforms” (p. 5). Furthermore the paper presents challenges associated with linking different kinds of sensors in a system, such as incompatibility with each other or the system architecture, data synchronization and amount of data (pp. 37-38).

Sensors also play an important role in the Internet of Things in which “physical items are no longer disconnected from the virtual world, but can be controlled remotely and can act as physical access points to Internet services” (Mattern & Floerkemeier, 2010, p. 242). Mattern & Floerkemeier specifically go into detail about the role of RFID (radio-frequency identification), which may be connected to sensors in order to easily communicate the sensor data to other devices.

### Sensors in games

Sensors can be used in videogames as an alternative to more traditional inputs. “This makes the system more autonomous, and can free the user from tedious input tasks” (Lundgren & Björk, 2003, § 2.1 para. 2). As D. M. Johnson & Wiles (2003) found, simplifying input commands, as one might by using sensors, can increase concentration and engagement in the player (§ 2.1 para. 2).

This idea is not unprecedented: In the last years, gesture-based computing was introduced to many people through the Nintendo Wii – which used as its primary form of input a wireless controller that has its position tracked via an infrared sensor, allowing users to control the software by moving the controller itself – and touch-based systems like smartphones (L. Johnson et al., 2011, p. 24). The Microsoft Kinect went even further: A depth sensor and color camera allowed for skeletal tracking and facial recognition, while a four-microphone array permitted voice recognition (Zhang, 2012, p. 4). Because of its capabilities and comparatively low price point, the Kinect even saw application outside of gaming, e.g. for coarse patient setup in Radiation Therapy (Bauer, Wasza, Haase, Marosi, & Hornegger, 2011).

There is however potential for games to utilize an even wider array of different sensors. Xu et al. (2009) developed a system in which a combination of electromyogram-based gesture recognition and an accelerometer could be used to solve a virtual Rubik’s Cube, while Lundgren & Björk (2003, § 5.4) cite biofeedback games, which are controlled through biosensors attached to the user. Unlike the Rubik’s Cube described above, which attempts to emulate an analog game, these biofeedback games, through their unusual interfaces, are highly different from traditional videogames. As Wetzel (2013) notes: “Different sensors have different strengths and weaknesses that completely change the way a game might work.”

### Sensors in augmented reality

Since Augmented Reality consists of augmenting the user’s environment, applications depend on sensor data in order to obtain information about same environment.

While purely marker-based AR will usually depend on a camera and computer vision software, location-based AR depends on tracking systems which can take a variety of forms. As examples for “locationing” technology, Wetzel (2013) mentions “GSM cells, GPS, fiducial markers, natural feature tracking, NFC/RFID as well as WiFi and Bluetooth-based proximity sensing” (§ 2.1). Although the reliability of GPS in particular has previously been criticized, including by Wetzel et al. (2008, p. 178) (referring to problems during the TimeWarp application), FitzGerald et al. (2013) observe that technological advancements in recent years have brought the most advanced locating systems to sub-centimeter accuracy (p. 47).

The amount of available sensors is one reason for the increasing use of commercial mobile devices for Augmented Reality applications, with Schmitz et al. (2012) mentioning several sensor technologies, such as GPS, RFID readers, and cameras as now being standard features (p. 1). Still, Papagiannakis et al. (2008) argue for more sensor technology in MARS, defining as the “ultimate goal” the ability to use them “eyes-free and hands-free” while walking (p. 12). Bower et al. (2014) somewhat similarly expresses certainty that Augmented Reality (not explicitly referring to mobile AR) will come to include “new trigger types . . ., more intelligent input recognition . . . and increased sophistication of expression types” (p. 12).

An example of a sensor technology with major applicability for Augmented Reality that has not been fully realized is eye tracking, with few solutions currently available (Sharma et al., 2016, p. 36).

Oftentimes, different kinds of sensors are combined to improve the quality of AR experiences. As early as 1992, Robinett referred to HMDs as “a multisensory display technique . . . in which the visuals depicting the surrounding three-dimensional (3-D) virtual world are generated so as to match the user's voluntary head movements” (p. 230).

Researchers have long been expanding on this fundamental hybrid system with additional sensors, frequently utilizing (Extended) Kalman Filters in order to combine the sensor data (though Hol et al. (2006, § 1 para. 4) cite shortcomings of the available technology as the reason for this, which indicates that combination of sensor technology may be reduced as individual systems become more reliable). The Touring Machine (Feiner et al., 1997) made use of differential GPS in combination with a magnetometer and tilt sensor in order to track user location and orientation. Visual-based systems can similarly benefit from addition of sensors due to what (Papagiannakis et al., 2008, p. 11) referred to as their “complimentary nature”: You & Neumann (2001) combined a computer vision algorithm with an inertial sensor consisting of three orthogonal-rate gyroscopes. A hybrid system incorporating both approaches was created by Schall et al. (2009) and utilized a Differential GPS or Real-Time Kinematic based GPS, an inertial measurement unit (IMU) containing gyroscopes, magnetometers and accelerometers, and a visual orientation tracker.

The Microsoft HoloLens contains an even higher number of sensors, including an IMU, four “environment understanding cameras”, a depth camera, photo / video camera, a four-microphone array, and an ambient light sensor (“Introducing the Microsoft HoloLens Development Edition,” 2016), processed with a “dedicated sensor fusion processing unit” (Sharma et al., 2016, p. 19).

Finally, some Augmented Reality applications may use application-specific sensors, such as the ones related to expertise transfer listed by Sharma et al. (2016), the microphones used to detect the location of a ping pong ball by Ishii et al. (1999) or the sound sensor used by Wetzel et al. (2008) which evaluates flute notes as part of an Augmented Reality game. Specht et al. (2011) also name the affordance of Augmented Reality to visualize data the human senses cannot naturally pick up on, for instance “compass orientation, invisible light (infrared, ultraviolet, X-rays, etc.), ultrasound, or barometric pressure” (p. 118). Sensors related to this information would only make sense in specialized applications but within these could be highly valuable.

## Design Patterns

In order to create a framework for interactions in Augmented Reality, it is necessary to investigate existing structures for designing systems. One of such structure, which has been applied to a number of related fields. This paper will first describe patterns in general and then how they have been used in games and within the domain of Augmented Reality specifically. Design patterns are a concept first proposed for use in architecture. They describe precisely how to use design techniques in order to achieve certain positive effects, at the same time providing insight and creating a shared vocabulary in the form of a pattern language (McGee, 2007; Wetzel, 2013). More precisely, design patterns “express a relationship between particular design contexts, forces (psychological, social, or structural constraints), and desired (‘positive’ or good) features” (McGee, 2007, § 1 para. 3). The core goals of pattern languages, according to Wetzel (2013, § 4 para. 1) are communication, analysis, creativity and improvement.

While patterns are prescriptive, the emergence of new patterns is assumed to be a result of trial and error (McGee, 2007, § 1 para. 6), or as (Wetzel, 2013) puts it: “In order for something to qualify as a pattern, it has to have been applied in several examples already. Otherwise one might argue that it does not constitute a real pattern” (§ 7 para. 1). (Wetzel then distinguishes between *established, emergent* and *hidden* patterns.)

Since their creation, design patterns have been applied to several different fields while largely retaining these core principles. Borchers (2001) presents a domain-independent, formal syntactic definition of pattern languages as directed acyclical graphs, in which each node (pattern) consists of a name, ranking, illustration, problem with forces, examples, solution, and diagram. This definition is further clarified in a set of semantics.

An example for patterns which slightly strayed from this approach are the game design patterns by Björk and Holopainen. According to McGee (2007, § 1 para. 9), these are more descriptive and concerned with idea generation. Cases like this make the definition of patterns somewhat difficult, especially when taking into account related but distinct concepts such as design rules “which offer advice and guidelines for specific design situations” (Zagal, Mateas, Fernández-Vara, Hochhalter, & Lichti, 2005, p. 1).

McGee (2007, § 2 para. 7) outlines the general characteristics of patterns as:

* Operational and precise
* Positive
* Flexible
* Debatable (the Pattern is clear enough to criticize)
* Testable
* End-user oriented

### Patterns for Games

Patterns for game design were first proposed by Kreimeier (2002). Calling for “a formal means to document, discuss, and plan” (para. 1) game design, as well as a shared vocabulary and rules for combining these elements, Kreimeier distinguishes these “content patterns” from software engineering patterns, which are concerned with how to write code, or process patterns, used in project management (para. 9). Kreimeier reasons that the existence of a game design pattern language would allow for efficient communication, documentation and analysis “e.g. for purposes of comparative criticism, re-engineering, or maintenance” (“What are patterns?”).

A topic closely related to patterns is that of game mechanics. This term, developed within the game design community, is defined by Lundgren & Björk (2003) as “any part of the rule system of a game that covers one, and only one, possible kind of interaction that takes place during the game, be it general or specific” (§ 3.1 para. 1). Mechanics differ from patterns in several ways: As Lundgren & Björk state, mechanics describe only solutions while a pattern additionally contains problems and methods; mechanics (both the term (which has also been used in reference to programming (§ 3.1 para. 2)) and its object) are not precisely defined or structured in relation to one another (§ 9 para. 2); and finally the effects a mechanic may have on a player experience are secondary or not described at all (§ 7.1 para. 1).

Addressing these concerns, Björk & Holopainen went on to formally create a collection of game design patterns. As mentioned above and reaffirmed by Wetzel (2013) “these game design patterns follow less of a strict problem-solution approach but rather describe identified game mechanics, their uses, occurrences and consequences” (§ 2.2 para. 3).

A conceptually similar approach was taken by Zagal et al. (2005). In the Game Ontology Project, they set out to create an alternative way to describe, analyze and study games, with pattern-like entries existing in a hierarchy the top level of which includes interface, rules, entity manipulation, and goals. Zagal et al. also emphasize that these are not criteria for creating good games (p. 2). An entry is defined by title, description, strong and weak examples, parent and potential child elements, and potentially elements that the entry is a part of (p. 5). The ontology is based on methods from prototype theory and grounded theory.

### Patterns for Augmented Reality and Augmented Reality Games

The literature review revealed only a few pattern approaches for the general domain of Augmented Reality. In addition, the results were not design patterns but *interaction patterns*, a term that is not strictly defined in the literature. Although the examples below are presented informally by name only, they may be argued to fit McGee’s characteristics (see section 2.3); regardless, they provide data which the framework presented in this paper may build on and have thus been included.

Ternier, De Vries, et al. (2012, § 2 para. 1) refer to the “Point Of Interest” (POI) interaction pattern implemented in mobile Augmented Reality browsers. When arriving at pre-defined points (making this an interaction pattern for location-based AR), users receive information about the environment through a choice of channels. Every user is treated the same way. According to FitzGerald et al. (2013, p. 47), browsers may also point the user towards nearby points of interest. Although one has to be present in order to perceive the information relayed at a POI, POIs can be set regardless of the creator’s location at any time (Munnerley et al., 2012, p. 44).

Lamantia (2009, "Painting with a Limited Palette") presents four interaction patterns, pertaining to how information is presented to the user. The *Head-Up Display* (HUD) presents information from a fixed point of view, i.e. the information is not assigned some coordinate in 3D space; normally this will align with the user’s field of view. The *Tricorder* interaction pattern overlaps with the Point Of Interest pattern described above; it refers to scenarios in which information is scanned from the environment by directing the device at points of interest, adding “pieces of information to an existing real-world experience, representing them directly within the combined, augmented-reality, or mixed-reality experience” (“Tricorder” para. 2). *Holochess* experiences consist of presenting entirely virtual objects to the AR environment. The last interaction pattern Lamantia brings up is essentially Obscured Information Visualization (see section 2.1.3.1). *X-Ray Vision-*based experiences “[simulate] seeing beneath the surface of objects, people, or places” (“X-Ray Vision” para. 1).

There have been multiple propositions and first attempts at design patterns for Augmented Reality games, however no comprehensive list has as of yet come of it.

Schmitz et al. (2012) attempted to map design patterns for mobile games (themselves based on Björk & Holopainen’s work) to cognitive and motivational effects in educational AR games. (It is worth pointing out that Augmented Reality is itself one of these mobile game patterns.) Although it is not included in the mobile games pattern language, Schmitz et al. also investigated the effects of the pattern “Roleplaying”, stating that it “seems to be highly relevant for the design of AR learning games” (p. 3).

Antonaci et al. (2015) discuss the application and development of patterns for Augmented Reality serious games. At the end of the paper, the authors present a short, preliminary list of patterns “which take advantage of AR potential” (p. 7); these are however not full patterns in that they consist of only names and short descriptions. This list consists of: Localization, Video recording and view sharing, synchronous communication, contextualization, and object recognition.

One of the inspirations for Antonaci et al. (2015) are the patterns for mobile mixed reality games proposed by Wetzel (2013). These patterns, Wetzel stresses, are not intended only for game design considerations but also “other aspects of mobile mixed reality games, namely authoring, content creation, interfaces, orchestration as well as testing and logging” (Abstract). The structure Wetzel settles on differs slightly from traditional design, consisting of: Name, categories, problem, solution, examples, description, effects, and connections to other patterns.

Although they did not use the term pattern, Wetzel et al. (2008) already treaded similar ground with their “Guidelines for Designing Augmented Reality Games.” These guidelines have easily identifiable names with descriptions which contain examples and take the form of solutions to specific design problems. Examples include “Experience First, Technology Second,” “Use the Real Environment,” and “Choose your tracking wisely” (pp. 177-179).

## Conclusion

Roland: Als Abschluss des Literaturkapitels fehlt mir noch eine kurze Zusammenfassung mit Bezug zu Deiner Arbeit: welche Ergebnisse nimmst Du mit, worauf baust Du auf, wovon grenzt Du Dich ab, was wird vertieft? Dazu reichen vermutlich 1-2 Absätze

„Zusammenfassung des Literaturkapitels, wo Du nochmal knapp beschreibst, was Du aus dem diskutierten mitnimmst: welche Patterns, welche Sensoren, welche Interaktionsformen/Visualisierungen?“

# Development of a framework for sensor-supported augmented reality games

The second contribution this thesis sets out to make is a taxonomy of user interactions in Augmented Reality utilizing sensors, based on patterns. Afterwards, the author attempts to exemplarily translate some of the found interactions into a framework for the Unity game engine, for use with the Microsoft HoloLens.

As in the study by Biocca & Rolland (1998), it is important to emphasize that the approach taken in this paper is that of the design sciences to “create technological artifacts that augment human ability (Biocca, 1996), not ones that manipulate human abilities solely for the purpose of experimentation and observation” (p. 265).

Additionally, mirroring approaches to game design patterns described above, this is not an attempt to instruct developers on what techniques to use but simply a classification of possible interactions, akin to the game mechanic terminology. To avoid confusion associated with the use of *game mechanics* to refer to techniques on a software level (as the classification in this thesis is strictly one of game design and the integration of these techniques into a game engine is simply a proof of concept), the “equivalent” (Lundgren & Björk, 2003, § 3.1 para. 2) term *mechanism* is used.

## Conception

With the primary basis for this taxonomy being design patterns, it is reasonable to first look at approaches to the creation of patterns and then adapt these principles to the task at hand.

The method for creating patterns laid out by Christopher Alexander (for use in architecture), as summarized by (McGee, 2007), follows these steps:

* Notice a situation “where one feels good.”
* Identify the cause.
* Articulate it in a way so the feature’s presence in other structures can be binarily identified.
* Identify “the conflicting Forces it resolves.”
* Identify relevant contexts
* Empirical tests (of the reactions presence and absence of the feature causes)

Thematically, the work by (Sharma et al., 2016) can serve as a basis for the framework. They mapped low level functions such as gaze, voice, or hand gestures to associated sensors for use with Augmented Reality and provide an overview of common issues different sensors might encounter. The design synthesis approach utilized in the paper may inspire work on this framework. A list of transfer mechanisms, although intended for expertise transfer, could also prove useful. Finally, they provide a list of challenges in combining different sensors in one system; compatibility with other sensors (for example interference caused by multiple devices using infra-red light) is an example of a category that differentiates the sensor-supported game mechanism framework from previous work.

# References

Antonaci, A., Klemke, R., & Specht, M. (2015). Towards Design Patterns for Augmented Reality Serious Games. In *The Mobile Learning Voyage - From Small Ripples to Massive Open Waters* (pp. 273–282). https://doi.org/10.1007/978-3-319-25684-9\_20

Azuma, R. T. (1997). A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments*, *6*(4), 355–385. Retrieved from http://www.dca.fee.unicamp.br/~leopini/DISCIPLINAS/IA369T-22014/Seminarios-entregues/Grupos-Visualização/Visualizacao-Gr-LuisPattam-paperdeapoio-1.pdf

Azuma, R. T., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent advances in augmented reality. *IEEE Computer Graphics and Applications*, *21*(6), 34–47. https://doi.org/10.4061/2011/908468

Bauer, S., Wasza, J., Haase, S., Marosi, N., & Hornegger, J. (2011). Multi-modal Surface Registration for Markerless Initial Patient Setup in Radiation Therapy using Microsoft’s Kinect Sensor. In *Proc. IEEE Workshop on Consumer Depth Cameras for Computer Vision (CDC4CV)* (pp. 1175–1181). IEEE Press. Retrieved from http://www5.informatik.uni-erlangen.de/Forschung/Publikationen/2011/Bauer11-MSR.pdf

Benko, H., Holz, C., Sinclair, M., & Ofek, E. (2016). NormalTouch and TextureTouch : High-fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (pp. 717–728). ACM. https://doi.org/10.1145/2984511.2984526

Biocca, F. A., & Rolland, J. P. (1998). Virtual Eyes Can Rearrange Your Body: Adaptation to Visual Displacement in See-Through, Head-Mounted Displays. *Presence: Teleoperators and Virtual Environments*, *7*(3), 262–277. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.541.8417&rep=rep1&type=pdf

Borchers, J. O. (2001). A Pattern Approach to Interaction Design. *AI & Society*, *15*(4), 359–376. Retrieved from https://guzdial.cc.gatech.edu/hci-seminar/uploads/1/BorchersInteractionPatterns.pdf

Bower, M., Howe, C., McCredie, N., Robinson, A., & Grover, D. (2014). Augmented Reality in education – cases, places and potentials. *Educational Media International*, *51*(1), 1–15. https://doi.org/10.1080/09523987.2014.889400

Calo, R., Denning, T., Friedman, B., Kohno, T., Magassa, L., McReynolds, E., … Woo, J. (2015). Augmented Reality: A Technology and Policy Primer. Retrieved from http://techpolicylab.org/wp-content/uploads/2016/02/Augmented\_Reality\_Primer-TechPolicyLab.pdf

Chandler, D., & Munday, R. (2011). augmented reality. In *A Dictionary of Media and Communication*. Oxford University Press. Retrieved from http://www.oxfordreference.com/view/10.1093/acref/9780199568758.001.0001/acref-9780199568758-e-0171

Crecente, B. (2016). Pokémon Go breaks iTunes record, Apple confirms. Retrieved December 27, 2016, from http://www.polygon.com/2016/7/22/12258490/pokemon-go-itunes-record-apple-confirms

Dasarathy, B. V. (1997). Sensor fusion potential exploitation-innovative architectures and illustrative applications. *Proceedings of the IEEE*, *85*(1), 24–38. https://doi.org/10.1109/5.554206

Dede, C. (2009). Immersive Interfaces for Engagement and Learning. *Science*, *323*(5910), 66–69. Retrieved from https://pdfs.semanticscholar.org/844a/742b416bf914c3e22e6a0c3d9f7f1d58a185.pdf

Dunleavy, M. (2014). Design Principles for Augmented Reality Learning. *TechTrends*, *58*(1), 28–34. https://doi.org/10.1007/s11528-013-0717-2

Dunleavy, M., Dede, C., & Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. *Journal of Science Education and Technology*, *18*(1), 7–22. https://doi.org/10.1007/s10956-008-9119-1

Feiner, S., MacIntyre, B., Höllerer, T., & Webster, A. (1997). A Touring Machine: Prototyping 3D Mobile Augmented Reality Systems for Exploring the Urban Environment. *Personal Technologies*, *1*(4), 208–217. Retrieved from https://www.researchgate.net/profile/Blair\_Macintyre/publication/221240775\_A\_Touring\_Machine\_Prototyping\_3D\_Mobile\_Augmented\_Reality\_Systems\_for\_Exploring\_the\_Urban\_Environment/links/0f31753c5290d35949000000.pdf

FitzGerald, E., Ferguson, R., Adams, A., Gaved, M., Mor, Y., & Thomas, R. (2013). Augmented reality and mobile learning: the state of the art. *International Journal of Mobile and Blended Learning*, *5*(4), 43–58. Retrieved from http://oro.open.ac.uk/38386/8/\_\_userdata\_documents4\_ctb44\_Desktop\_FitzGerald paper-IJMBL 5%284%29.pdf

Fitzgerald, E., Taylor, C., & Craven, M. (2013). To the Castle! A comparison of two audio guides to enable public discovery of historical events. *Personal and Ubiquitous Computing*, *17*(4), 749–760. https://doi.org/10.1007/s00779-012-0624-0

Furmanski, C., Azuma, R. T., & Daily, M. (2002). Augmented-reality visualizations guided by cognition: Perceptual heuristics for combining visible and obscured information. In *Proceedings of the International Symposium on Mixed and Augmented Reality (ISMAR’02)*. IEEE. https://doi.org/10.1109/ISMAR.2002.1115091

Henderson, S. J., & Feiner, S. (2009). Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret. In *IEEE International Symposium on Mixed and Augmented Reality 2009* (pp. 135–144). IEEE. https://doi.org/10.1109/ISMAR.2009.5336486

Hol, J. D., Schön, T. B., Gustafsson, F., & Slycke, P. J. (2006). Sensor Fusion for Augmented Reality. In *2006 9th International Conference on Information Fusion* (pp. 1–6). IEEE. https://doi.org/10.1109/ICIF.2006.301604

Introducing the Microsoft HoloLens Development Edition. (2016). Retrieved December 29, 2016, from https://www.microsoft.com/microsoft-hololens/de-de/development-edition

Ishii, H., Wisneski, C., Orbanes, J., Chun, B., & Paradiso, J. (1999). PingPongPlus: design of an athletic-tangible interface for computer-supported cooperative play. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM. https://doi.org/http://doi.acm.org/10.1145/302979.303115

Johnson, D. M., & Wiles, J. (2003). Effective Affective User Interface Design in Games. *Ergonomics*, *46*(13/14), 1332–1345. Retrieved from http://eprints.qut.edu.au/6693/1/6693.pdf

Johnson, L., Adams Becker, S., Cummins, M., Estrada, V., Freeman, A., & Hall, C. (2016). *NMC Horizon Report: 2016 Higher Education Edition.* Austin, Texas: The New Media Consortium. Retrieved from http://cdn.nmc.org/media/2016-nmc-horizon-report-he-EN.pdf

Johnson, L., Smith, R., Willis, H., Levine, A., & Haywood, K. (2011). *The 2011 Horizon Report*. Austin, Texas: The New Media Consortium. Retrieved from http://www.nmc.org/pdf/2011-Horizon-Report.pdf

Julier, S., Lanzagorta, M., Baillot, Y., Rosenblum, L., Feiner, S., Höllerer, T., & Sestito, S. (2000). Information filtering for mobile augmented reality. In *Proceedings - IEEE and ACM International Symposium on Augmented Reality, ISAR 2000* (pp. 3–11). IEEE. https://doi.org/10.1109/ISAR.2000.880917

Kreimeier, B. (2002). The Case For Game Design Patterns. Retrieved December 14, 2016, from http://www.gamasutra.com/view/feature/4261/the\_case\_for

Kruijff, E., Swan II, J. E., & Feiner, S. (2010). Perceptual Issues in Augmented Reality Revisited. Retrieved from http://www.icg.tu-graz.ac.at/Members/kruijff/perceptual\_issues\_AR.pdf

Lamantia, J. (2009). Inside Out: Interaction Design for Augmented Reality. Retrieved December 19, 2016, from http://www.uxmatters.com/mt/archives/2009/08/inside-out-interaction-design-for-augmented-reality.php

Lundgren, S., & Björk, S. (2003). Game Mechanics: Describing Computer-Augmented Games in Terms of Interaction. In *Proceedings of TIDSE ’03*. Retrieved from http://www.cse.chalmers.se/research/group/idc/publication/pdf/lundgren\_bjork\_game\_mechanics.pdf

Mattern, F., & Floerkemeier, C. (2010). From the Internet of Computers to the Internet of Things. In K. Sachs, I. Petrov, & P. Guerrero (Eds.), *From Active Data Management to Event-Based Systems and More (Lecture Notes in Computer Science, 6462)* (pp. 242–259). Springer Berlin Heidelberg. Retrieved from http://ruangbacafmipa.staff.ub.ac.id/files/2012/02/ebooksclub.org\_\_From\_Active\_Data\_Management\_to\_Event\_Based\_Systems\_and\_More.pdf#page=258

McGee, K. (2007). Patterns and Computer Game Design Innovation. In *Proceedings of the 4th Australasian conference on Interactive entertainment*. RMIT University. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.90.29&rep=rep1&type=pdf

Milgram, P., & Kishino, F. (1994). Taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, *77*(12), 1321–1329. Retrieved from https://cs.gmu.edu/~zduric/cs499/Readings/r76JBo-Milgram\_IEICE\_1994.pdf

Mulloni, A., Dünser, A., & Schmalstieg, D. (2010). Zooming Interfaces for Augmented Reality Browsers. In *Proceedings of the 12th international conference on Human computer interaction with mobile devices and services* (pp. 161–170). New York: ACM. https://doi.org/10.1145/1851600.1851629

Munnerley, D., Bacon, M., Wilson, A., Steele, J., Hedberg, J., & Fitzgerald, R. (2012). Confronting an augmented reality. *Research in Lerning Technology*, *20*, 39–48. https://doi.org/10.3402/rlt.v20i0.19189

Niantic. (2013). Ingress. San Francisco, CA: Niantic.

Niantic. (2016). Pokémon GO. San Francisco, CA: Niantic.

Nilsson, S., Johansson, B., & Jönsson, A. (2009). Using AR to support cross-organisational collaboration in dynamic tasks. In *In Proceedings of the 8th IEEE International Symposium on Mixed and Augmented Reality, ISMAR* (pp. 3–12). Washington, DC: IEEE Computer Society. https://doi.org/10.1109/ISMAR.2009.5336522

Olshannikova, E., Ometov, A., Koucheryavy, Y., & Olsson, T. (2015). Visualizing Big Data with augmented and virtual reality: challenges and research agenda. *Journal of Big Data*, *2*(1). https://doi.org/10.1186/s40537-015-0031-2

Papagiannakis, G., Singh, G., & Magnenat-Thalmann, N. (2008). A survey of mobile and wireless technologies for augmented reality systems. Retrieved from http://calhoun.nps.edu/bitstream/handle/10945/41253/Singh\_d912f5075af50e0812\_2008.pdf?sequence=1

Radu, I. (2014). Augmented reality in education: a meta-review and cross-media analysis. *Personal and Ubiquitous Computing*, *18*(6), 1533–1543. https://doi.org/10.1007/s00779-013-0747-y

Robinett, W. (1992). Synthetic experience: a proposed taxonomy. *Presence: Teleoperators and Virtual Environments*, *1*(2), 229–247.

Schall, G., Wagner, D., Reitmayr, G., Taichmann, E., Wieser, M., Schmalstieg, D., & Hofmann-Wellenhof, B. (2009). Global Pose Estimation using Multi-Sensor Fusion for Outdoor Augmented Reality. In *Proceedings of the 2009 8th IEEE International Symposium on Mixed and Augmented Reality* (pp. 153–162). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.156.6860&rep=rep1&type=pdf

Schell, J. (2015). VR and AR: 2016, 2020, 2025. Retrieved December 26, 2016, from https://www.youtube.com/watch?v=wD0bp0r-EpI

Schmitz, B., Specht, M., & Klemke, R. (2012). An Analysis of the Educational Potential of Augmented Reality Games for Learning. In M. Specht, J. Multisilta, & M. Sharples (Eds.), *Proceedings of the 11th World Conference on Mobile and Contextual Learning 2012* (pp. 140–147). Retrieved from http://dspace.ou.nl/handle/1820/4790

Sensor. (n.d.). Retrieved December 29, 2016, from https://www.merriam-webster.com/dictionary/sensor

Sharma, P., Wild, F., Klemke, R., Helin, K., & Azam, T. (2016). *D3.1 Requirement analysis and sensor specifications – First version*. (F. Wild & P. Sharma, Eds.).

Spatial mapping. (n.d.). Retrieved January 4, 2017, from https://developer.microsoft.com/en-us/windows/holographic/spatial\_mapping

Specht, M., Ternier, S., & Greller, W. (2011). Dimensions of Mobile Augmented Reality for Learning: A First Inventory. *Journal of the Research Center for Educational Technology (RCET)*, *7*(1), 117–127. Retrieved from http://rcetj.org/index.php/rcetj/article/viewFile/151/241

Sutherland, I. E. (1968). A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, fall joint computer conference, part I* (pp. 757–764). https://doi.org/10.1145/1476589.1476686

Ternier, S., De Vries, F., Börner, D., & Specht, M. (2012). Mobile augmented reality with audio, supporting fieldwork of Cultural Sciences students in Florence. In G. Eleftherakis, M. Hinchey, & M. Holcombe (Eds.), *Software Engineering and Formal Methods - Proceedings of 10th International Conference, SEFM 2012* (pp. 367–379). Springer. Retrieved from http://dspace.ou.nl/handle/1820/5034

Ternier, S., Klemke, R., Kalz, M., van Ulzen, P., & Specht, M. (2012). ARLearn: Augmented reality meets augmented virtuality. *Journal of Universal Computer Science*, *18*(15), 2143–2164. https://doi.org/10.3217/jucs-018-15-2143

Wetzel, R. (2013). A Case for Design Patterns supporting the Development of Mobile Mixed Reality Games. *Foundations of Digital Games*. Retrieved from http://www.fdg2013.org/program/workshops/papers/DPG2013/b6-wetzel.pdf

Wetzel, R., McCall, R., Braun, A.-K., & Broll, W. (2008). Guidelines for Designing Augmented Reality Games. In *Proceedings of the 2008 Conference on Future Play: Research, Play, Share* (pp. 173–180). Retrieved from http://eprints.lincoln.ac.uk/24599/1/Wetzel et al. - 2008 - Guidelines for designing augmented reality games.pdf

What is WEKIT? (n.d.). Retrieved January 2, 2017, from http://wekit.eu/

White, R. M. (1987). A Sensor Classification Scheme. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, *34*(2), 124–126. Retrieved from http://ijlalhaider.pbworks.com/w/file/fetch/64130986/A Sensor Classification Scheme.pdf

Xu, Z., Xiang, C., Wen-Hui, W., Ji-Hai, Y., Lantz, V., & Kong-Qiao, W. (2009). Hand Gesture Recognition and Virtual Game Control Based on 3D Accelerometer and EMG Sensors. In *Proceedings of the 14th international conference on Intelligent user interfaces* (pp. 401–406). ACM. Retrieved from https://pdfs.semanticscholar.org/6878/79899cb5c520970fd76eaca8b79e4aee820d.pdf

Yamabe, T., & Nakajima, T. (2013). Playful training with augmented reality games: Case studies towards reality-oriented system design. *Multimedia Tools and Applications*, *62*(1), 259–286. https://doi.org/10.1007/s11042-011-0979-7

You, S., & Neumann, U. (2001). *Fusion of Vision and Gyro Tracking for Robust Augmented Reality Registration*. Retrieved from https://trac.v2.nl/export/5432/andres/Documentation/INS Kalman/fusion of vision and gyro tracking for AR.pdf

Zagal, J. P., Mateas, M., Fernández-Vara, C., Hochhalter, B., & Lichti, N. (2005). Towards an Ontological Language for Game Analysis. In *Proceedings of DiGRA 2005 Conference* (pp. 3–14). Retrieved from https://users.soe.ucsc.edu/~michaelm/publications/zagal-worlds-in-play-2007.pdf

Zhang, Z. (2012). Microsoft Kinect Sensor and Its Effect. *IEEE Multimedia*, *19*(2), 4–10. Retrieved from https://www.researchgate.net/profile/Zhengyou\_Zhang/publication/254058710\_Microsoft\_Kinect\_Sensor\_and\_Its\_Effect/links/00b7d53ab783285cdb000000.pdf

Declaration of authenticity

# Appendix